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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A specialists meeting on atomization and nondilute spray behavior with 36 participants was held at Sandia National Laboratories, Livermore, California on 20-21 March 1985. Dilute sprays, nondilute sprays, atomization and measurement techniques each were discussed in two-hour topical sessions. Two subsequent discussion periods were used for general discussions and recommendations for future research. Twenty four recommendations were made. Originator supplied keywords include:

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Additional keywords include: Fuel Sprays, Fuel injection, Combustion, Jet atomization.

SUMMARY REPORT

Specialists Meeting on Atomization and Non-dilute Spray Behavior
held at Sandia National Laboratories on 20-21 March 1985

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Table of Contents

1.0 Introduction

A Specialists Meeting on Atomization and Non-dilute Spray Behavior was held on March 20 and 21, 1985 at Sandia National Laboratories. The meeting was jointly sponsored by the Air Force Office of Scientific Research, the Army Research Office and Sandia National Laboratories. The convening of the meeting was motivated by the perception that the areas of atomization and non-dilute spray behavior were technologically important, poorly understood and little studied. It was the expectation of the sponsors that, by providing a forum for experts to review the current state of knowledge and identify critical deficiencies, it would be possible to establish directions and priorities for increasing the research in these areas.

Attendance at the meeting was by invitation only. This was done to keep the number of attendees small enough to promote active discussion and participation from all. An attempt was made to include researchers who were representative of current activity in spray research, as well as those working in potentially relevant areas. The List of Attendees is included as Appendix A.

The meeting was organized into six sessions. The first four, Dilute Spray Behavior, Non-dilute Spray Behavior, Atomization, and Measurement Techniques, were designed to review past and current research and provide a framework for the last two sessions. These were a General Discussion of the material presented in the four reviews and final session devoted to developing a Summary and Research Recommendations resulting from the meeting. In the subsequent sections of this report, each of the review sessions is summarized, followed by a synopsis of the recommended research needs in the field. The Figures used by the four invited speakers are included as Appendices B through E. These Figures are referenced in the following summary sections.

2.0 Dilute Sprays

The summary of Dilute Spray Behavior was given by Professor Gerard Faeth of Pennsylvania State University. The lecture was intended to preface the areas of major concern for the meeting by reviewing results in a spray regime in which research directions were relatively well defined and not in need of further stimulation. In fact, even this presentation caused considerable discussion among the participants.

The fourth figure (see Appendix B) of Professor Faeth's presentation defines dilute sprays based on behavioral limitations. This figure provoked a strong controversial response. It became clear that the boundary between dilute and non-dilute behavior itself is a significant unknown and may be coupled to the spray phenomenon of interest. Thus, the boundary for droplet interactions influencing evaporation or group mode combustion may differ from that for turbulence modulation. Figure 4 then may be regarded as a general rule of thumb, reflecting conditions which may be neither necessary nor sufficient for dilute spray behavior.

Figures 8-11 identify three approaches to modeling spray behavior. These approaches reflect contemporary capability for predicting turbulent flow behavior in which drop sizes are much smaller than grid resolution of computers. Therefore, spray behavior has been modeled as a subgrid phenomenon using Reynolds or Favre-averaged differential transport equations with various levels of closure. The results given in Professor Faeth's presentation all were calculated with the k-epsilon closure model.

The first of the three models for particle-laden flows, illustrated in the eighth presentation figure, is the locally homogeneous flow (LHF) model. In this model discrete particle phenomena are ignored, and the particulate is modeled as a jet of a second fluid continuum injected into the ambient fluid. The model is rigorously valid only for infinitely small particles at low volume fractions.

The second model discussed by Professor Faeth and illustrated in Figure 9 is the discrete separated flow (DSF) model. In this model a particle laden flow is simulated by a computationally tractable number of discrete particles. Mass, momentum and energy exchanges between the particle and the fluid ambient are influenced by the mean velocity of the fluid flow and not by ambient turbulence behavior.

The last of the three models, shown in the tenth figure, is the stochastic separated flow (SSF) model. It differs from the DSF class of models in that ambient turbulence does influence particle behavior through a random sampling of turbulent eddy behavior.

Figures 14-19, 20-22, 23-25, 26-28 and 29-39 show, respectively, comparisons between the predictions of the three models and experimental measurements for the particle-laden flows listed in Figure 13. Note that solid particles in air and gaseous bubbles in liquid were tested along with liquid sprays in air. The SSF model predictions generally are quite accurate and outperform the other models. Some inaccuracies are noteworthy for SSF predictions of radial dispersion, but these errors are attributed to the inability of the k-epsilon closure model to account for anisotropic turbulence. These predictions reflect contemporary spray prediction capability.

Outstanding research issues for dilute spray behavior are summarized in Figure 57. Figures 42-56 reflect the current state of understanding for these issues, including research programs which are currently active. These Figures suggest that significant research remains for single droplet and dilute spray behavior. A strong coupling exists to the atomization and nondilute phenomena, which initialize the aerothermochemical behavior of dilute sprays.

3.0 Non-dilute Sprays

The review of non-dilute sprays was given by Professor C. K. Law of the University of California, Davis. Suggested references were the review article by Faeth (Reference 1) and the paper by O'Rourke and Bracco (Reference 6).

As shown in Figure 3 (see Appendix C), the non-dilute or dense spray is a transition state between the atomization region and the dilute spray. In this region the droplet density is high so that droplet-droplet interactions are important. Further, the spray is not fully mixed with the ambient. Thus there are substantial radial temperature and velocity gradients and droplets are moving at moderate Reynolds numbers. The extent of the non-dilute spray region is primarily governed by the rate of ambient entrainment and mixing. The spray is dilute when the inter-droplet spacing has increased to the point that droplets may be considered as interacting with the intervening fluid instead of each other. A code developed for the non-dilute spray region should be capable of treating the evolution of the initial droplet size and momentum distributions, as given by the appropriate atomization model. At present, this initial input is largely empirical.

Non-dilute sprays have been regarded as presenting a more difficult challenge for analysis than dilute sprays because of phenomena described in the current summary. Dr. Law suggested that opportunities for simplifications in analyses in non-dilute sprays also should be explored (see Figures 6 and 7). For example, the interior of the spray may be relatively cool and saturated with vapor so that mass transfer and change of phase effects can be ignored.

While there may be differences in approach to the detailed modeling, there appears to be agreement on the important processes which must be treated in a description of non-dilute sprays. These are droplet collision, droplet transport, and two-phase flow interactions.

Droplet collisions may result in coalescence (see Figures 14-20), with one resultant large droplet, partial coalescence followed by separation, resulting in the change in sizes of collision partners and/or the creation of new droplets, or inelastic recoil, with no change in size. Coalescence is governed by the rotational energy of the collision complex. If the rotational energy of the complex exceeds the increased surface energy necessary to form two droplets, the complex will be unstable and separate. There is little quantitative information on the other possible processes. Therefore, the inclusion of droplet-droplet interactions involves the development of approximate, largely intuitive models for collision effects.

Droplet transport processes in non-dilute sprays must be modeled over the range spanning fluidized bed to non-interacting conditions. In addressing these problems, Dr. Law presented an extensive review of vaporization processes relevant to non-dilute sprays. This discussion is summarized in Figures 9-15. Approximate relations have been developed for drag coefficients, heat and mass transport rates in dense flows. However, these are largely based on data obtained for particulate or low vapor pressure fluids. Further research is needed to develop appropriate relations for vaporizing droplets. Dense spray mass transport becomes particularly important for combusting flows. The dynamics of group, as opposed to individual droplet, combustion are governed by the fuel vaporization and transport rate from the fuel rich, dense spray to the outer, oxygen-rich mixing zone.

In the non-dilute spray region, the ambient gas is being accelerated and entrained by the high velocity droplet stream. Turbulence production is reduced due to particle inertia which also modifies turbulent transport (see Figure 21).

4.0 Atomization

The review of jet atomization was presented by Dr. Rolf Reitz of General Motors Research Laboratory and followed the general outline of Reference 11. While there appears to be no precise definition of atomization, for the purposes of this discussion, the term will be associated with that region of the injected fuel spray in which the fuel is reduced to droplets of size much less than the nozzle orifice. Thus, the atomization region can be considered as extending from an undefined point upstream of the nozzle orifice to the non-dilute region of the spray.

With other conditions held fixed, as shown in Figure 3 (see Appendix D), it has been possible to identify four distinct regimes of jet breakup which are a function of jet velocity. At very low speeds, the jet is unstable with respect to small perturbations and forms droplets of a size equal to or larger than the jet (Rayliegh instability regime). At slightly higher velocities, the jet experiences a low shear interaction with the ambient gas and jet breakup is augmented by the aerodynamic interaction between the liquid and gas (First wind-induced breakup regime). The droplet size is still on the order of the jet diameter. At higher velocities, jet breakup is due to the growth of unstable surface waves produced by the relative motion between the jet and ambient gas (Second wind-induced breakup regime). Since the wavelength of these disturbances is short, the resulting droplets are much less than the jet diameter. With the possible exception of the second wind-induced breakup regime, the above processes may have little to do with the formation of spray from practical fuel nozzles, since all three involve breakup at a considerable distance downstream of the nozzle exit. In contrast, both single and dual fluid (air assist) atomizers, when operating at their design points, appear to atomize the fluid almost instantaneously upon emergence of the jet from the nozzle. This final regime of jet breakup has been termed "atomization" and is characterized by high jet velocities and/or high relative gas-liquid velocities.

Also in contrast to the other three regimes, there is a lack of consensus on the mechanisms operating in the atomization regime. Due to small dimensions, the high liquid densities and other impediments to experimental investigation, there is little direct knowledge about the state of the liquid and gas in this region. Experimental studies have concentrated on elucidating the variables controlling the spray shape and droplet size distribution and then inferring the atomization mechanism(s) which are consistent with the data. While not inclusive, the proposed atomization mechanisms, Figure 11, can be reduced to six general types:

a. Aerodynamic interaction - This is similar to the wind-induced interaction models developed for lower speed jets. Primary breakup is attributed to wave growth on the liquid surface.

b. Pipe turbulence - Initial jet breakup is attributed to internal fluid motion produced by turbulence generated upstream of the nozzle.

c. Wall boundary layer profile rearrangement - Breakup forces are produced by the rearrangement of the fluid radial velocity profile once the jet exits the nozzle and the wall boundary condition is no longer present. The redistribution of energy results in radial velocity components which disrupt the jet.

d. Boundary layer acceleration - Fluid in the boundary layer accelerates due to the abrupt change in constraint at the nozzle exit. This acceleration produces interface stresses and surface waves leading to breakup.

e. Supply pressure oscillations - Jet instability and cross sectional variations are directly related to variations in the fluid supply pressure.

f. Cavitation - Cavitation, and resultant two-phase flow, upstream of the nozzle exit produce large pressure disturbances which lead to atomization.

Investigations of sprays produced by high pressure liquid jets injected into quiescent, room temperature air have yielded data which are consistent with the aerodynamic interaction model, if modified to empirically account for nozzle geometry (see Figures 12-20). However, the role of nozzle geometry is not well understood and a complete model for the atomization process could well involve components of cavitation and/or boundary layer effects. It should be noted that the reported agreement is not supported by direct measurement of the droplet size distribution in the atomization region. Such measurements have not been made. Rather, an assumed droplet size distribution, based on scaling appropriate to the modified aerodynamic breakup model, has been used, together with a non-dilute spray code, to predict the droplet size distribution in the dilute spray region, where measurements have been made. Clearly, there is a need for more direct methods of determining atomization mechanisms and for a theory capable of predicting the droplet size distribution.

Discussion of Dr. Reitz's presentation produced two criticisms of the results:

1. Theoretical prediction of initial drop sizes was based on a linearized stability analysis extended to interfacial wave amplitudes well beyond the linear regime.

2. Supporting experimental results for drop sizes are based on measurements of small numbers of drops at the spray perimeter, where flash photographs could be taken. The interior of the spray, containing most of the mass flow of liquid, could not be measured.

Dr. Reitz and his co-investigator, Dr. Bracco, responded that their studies represent the most advanced application of current scientific capability to a complex physical phenomenon of high technological relevance. The perceived shortcomings of this research should stimulate research to improve mathematical and instrumental capabilities.

5.0 Measurement Techniques

An overview of Spray Measurements, Methods and Applications was given by Dr. William Bachalo of Aerometrics, Inc. The text interspersed with Dr. Bachalo's presentation Figures makes additional direct commentary unnecessary. This presentation discussed generally the application of optical and physical probe measurement techniques for determining drop size and velocity in sprays. Dr. Bachalo concluded that the phase Doppler approach, which has been the subject of his research activity, offers superior capability with respect to the range of drop sizes measured without adjustments to optical components and measurements in high droplet number densities and large gas-phase index of refraction gradients. This conclusion was contested by Drs. Holve and Hess, who are investigating other methodologies for drop size and velocity measurement.

Dr. Bachalo's presentation reflects the mainstream of research activity on instrumentation for spray characterization. New requirements for instrumentation will arise in relation to atomization and non-dilute spray research.

Some demonstration of these requirements already has been given in the presentations by Drs. Law and Reitz. They would include the following:

1. Liquid volume fractions sufficiently high to discourage the use of electromagnetic radiation.

2. Interfacial geometries which are irregular and highly complex.

3. Highly transient behavior.

Also related to these requirements is the need to acquire, quantify and analyze information.

Dr. C. W. Kauffman made a brief presentation on neutron radiography--a measurement technique which has been demonstrated successfully under high liquid volume fraction conditions.

An overall assessment of Dr. Bachalo's presentation and related discussion is that measurement of drop size and velocity in dilute sprays is approaching credibility, although hampered by the lack of an accepted standard to test accuracy. Techniques for measuring atomization and non-dilute spray behavior are largely unexplored.

There are various methods for incorporating these effects depending upon the turbulence model employed. Particularly at high droplet densities, there is a lack of quantitative data to guide model development.

As has been noted in the above discussion, there are gaps in the understanding of non-dilute spray phenomena. At present, these gaps are being filled by approximations based on assumptions and extrapolations, largely from dilute spray behavior. Nonetheless, computer models, incorporating these approximations, have been shown to be consistent with overall spray behavior. While this may be partially fortuitous, it suggests that the overall approach is correct. However, better diagnostic techniques, capable of determining local gas and droplet properties in non-dilute sprays, are essential to provide detailed verification of the complex models now in use and under development.

6.0 Research Needs

During the last two sessions of the meeting, the attendees developed a list of the major research needs in the general area of sprays. As given, and ammended, these are:

1. Diagnostics for liquid scalar properties.

2. Control theory/dynamic sensing - this was recognized as an application of spray understanding.

3. Drop/turbulence interactions.

4. Interphase transport phenomena - two phase, including indirect drop-drop interaction.

5. Critical point phenomena

6. Aerodynamic drop shattering and distortion.

7. Transient drop ignition/extinction.

8. Diagnostic instrumentation for dense sprays.

9. Highly transient spray effects - not covered in this meeting.

10. Surface wave instability.

11. Cavitation within injectors.

12. Non-dilute combustion and structure.

13. Spray-related combustion instability.

14. Identification of modeling simplifications appropriate to various regimes.

15. Mechanisms of production of stable drops.

16. Selection of reference atomizers for laboratory studies.

17. Computational methods for two-phase flows.

18. Transverse injection - injection into cross flow.

19. Scaling of experiments.

20. Drop-drop interaction - collision, coalescence and shattering.

21. Surface interactions - drop with wall.

22. Liquid phase reactions - monopropellant, fuel/oxidizer.

23. Surface tension.

24. Atomization of non-Newtonian fluids.

It should be stressed that this is not a prioritized listing. No attempt was made to assign priorities to the various research needs. However, an examination of the list reveals that a large number of the items deal with aspects of atomization. This was probably predictable since, as was noted in the review presentation, atomization is the least understood of the spray phenomena.

7.0 References

One of the preliminaries to the meeting was a request for relevant background reference publications made to the invitees. The response to this request was truly overwhelming--enough papers were suggested to require weeks of careful study. A sampling of these papers was chosen for mailing to the attendees to provide a perspective on current spray research capability. This sampling is not intended to be comprehensive, and we offer our apologies to all of those submitters whose suggestions were not included.

Dilute Sprays

1. Faeth, G. M., "Evaporation and Combustion of Sprays," Progress in Energy and Combustion Science, Volume 9, 1983, Pages 1-76.

2. Kerstein, A. R., "Prediction of the Concentration PDF for Evaporating Sprays," International Journal of Heat and Mass Transfer, Volume 27, Number 8, 1984. Pages 1291-1309.

3. Sirignano, W. A., "Fuel Droplet Vaporization and Spray Combustion Theory," Progress in Energy and Combustion Science, Volume 9, 1983, Pages 291-322.

Nondilute Sprays

4. Koshland, K. P. and Bowman, C. T., "Combustion of Monodisperse Droplet Clouds in a Reactive Environment," Twentieth (International) Symposium on Combustion. Pittsburgh: The Combustion Institute, 1985.

5. Miyasaka, K. and Law, C. K., "Combustion of Strongly-Interacting Linear Droplet Arrays," Eighteenth (International) Symposium on Combustion. Pittsburgh: The Combustion Institute, 1981. Pages 283-292.

6. O'Rourke, P. J. and Bracco, F. V., "Modeling of Drop Interactions in Thick Sprays and a Comparison With Experiments," Paper presented at the Institution of Mechanical Engineers Stratified Charge Automotive Engines Conference, London, England, November 1980. Publication ISBN 0-85298-4693 of the Institute of Mechanical Engineers, England.

7. Soo, S. L., "Development of Dynamics of Multiphase Flow," International Journal of Science and Engineering, Volume 1, Number 1, 1984. Pages 13-29.

Atomization

8. Bogy, D. B., "Drop Formation in a Circular Liquid Jet," Annual Reviews of Fluid Mechanics, Volume 11, 1979. Pages 207-228.

9. Fritts, M. J., Fyfe, D. E. and Oran, E. S., "Numerical Simulations of Fuel Droplet Flows Using a Lagrangian Triangular Mesh," Naval Research Laboratory Memorandum Report 5408, September 21, 1984.

10. Lin, S. P. and Roberts, G., "Waves in a Viscous Liquid Curtain," Journal of Fluid Mechanics, Volume 112, 1981. Pages 443-458.

11. Reitz, R. D. and Bracco, F. V., "Mechanism of Atomization of a Liquid Jet," Physics of Fluids, Volume 25, Number 10, October 1982. Pages 1730-42.

12. Sellans, R. W. and Brzustowski, T. A., "A Prediction of the Droplet Size Distribution in a Spray From First Principles," Paper presented at the Combustion Institute Eastern States Section 1984 Fall Technical Meeting, Clearwater Beach, Florida, December 3-5, 1984.

Instrumentation

13. Bachalo, W. D., "Droplet Analysis Techniques: "Their Selection and Application," American Society for Testing and Materials, Special Technical Publication 848, 1984. Pages 5-21.

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APPENDIX B

Dilute Spray Behavior

Figures by G. M. Faeth

DILUTE SPRAY BEHAVIOR

G. M. FAETH

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THE PENNSYLVANIA STATE UNIVERSITY

AFOSR/ARO SPECIALISTS MEETING ON NONDILUTE SPRAYS

SANDIA COMBUSTION RESEARCH FACILITY

LIVERMORE, CA

20, 21 MARCH 1985

OUTLINE OF TALK

CHARACTERISTICS OF DILUTE SPRAYS

CONTEMPORARY SPRAY MODELS

STRUCTURE OF DILUTE DISPERSED FLOWS

RESEARCH ISSUES FOR DILUTE SPRAYS

CHARACTERISTICS OF DILUTE SPRAYS

DILUTE SPRAY REGION

ASSUMPTIONS

1. NEGLIGIBLE EFFECTS OF NEARBY DROPS ON INTERPHASE TRANSPORT RATES.

   LIQUID VOLUME FRACTION (LVF) < 1 - 10%

2. NEGLIGIBLE EFFECTS OF DROP COLLISIONS

   INTEGRAL SCALE/DROP COLLISION LENGTH $\sim x$ LVF/(4 d_p) $\ll 1$

3. ONLY ROUGHLY SPHERICAL DROPS PRESENT

REGION*

1. TWIN-FLUID INJECTORS, $x/d > 10 - 50$
2. PRESSURE-ATOMIZING INJECTORS, $x/d > 10 - 200$

---

*FOR OPERATION IN THE ATOMIZATION REGIME, ALONG AXIS OF SPRAY.

CONTEMPORARY SPRAY MODELS

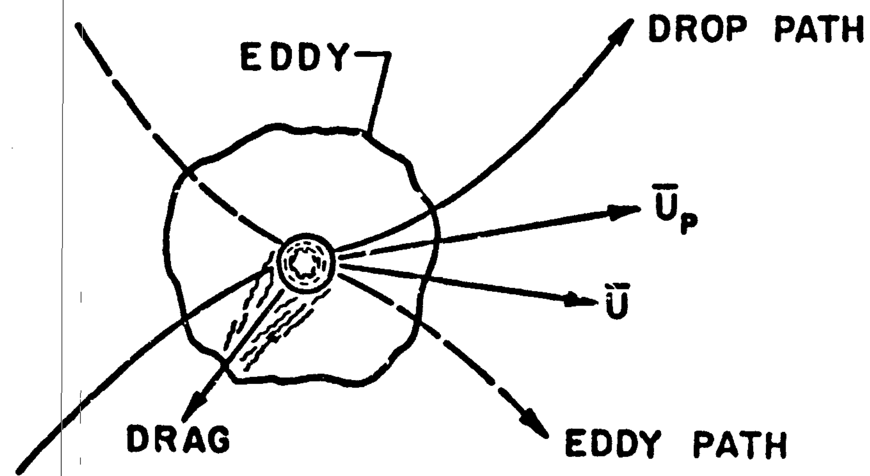
SPRAY MODELS IN INDUSTRY

FIRM	APPLICATION
ALLISON GAS TURBINE	AIRBREATHING PROPULSION
AVCO-LYCOMING	AIRBREATHING PROPULSION
BABCOCK AND WILCOX	STEAM POWER SYSTEMS
FACTORY MUTUAL RESEARCH CORP.	SPRINKLER SYSTEMS
GARRETT TURBINE ENGINE CO.	AIRBREATHING PROPULSION
GENERAL ELECTRIC CO.	AIRBREATHING PROPULSION
GENERAL MOTORS CORP.	AUTOMOTIVE
ROCKETDYNE	ROCKET ENGINES
UNITED TECHNOLOGIES CORP.	AIRBREATHING PROPULSION
WESTINGHOUSE CORP.	STEAM POWER SYSTEMS

PHASE INTERACTIONS: PARTICLE-LADEN FLOW

MEAN SOURCE TERM
DRAG IS EXCHANGED BETWEEN PHASES IN THE MEAN

TURBULENT DISPERSION
RANDOM DEFLECTION OF DROPS BY TURBULENCE

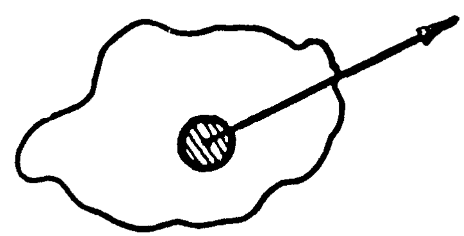


NONLINEAR PHASE INTERACTION
DRAG IS NOT A LINEAR FUNCTION OF SLIP VELOCITY, E.G.
$\overline{D} \neq D(\overline{U}_p - \overline{U})$

TURBULENCE MODULATION
EXTRACTION OF TURBULENCE ENERGY BY DROP DRAG

Locally Homogeneous Flow (LHF) Model

Assumption: Infinitely fast interphase transport rates, i.e., particle and continuous phase velocities are always identical.



$$(\bar{u} + u')_i = (\bar{u}_p + u_p')_i$$

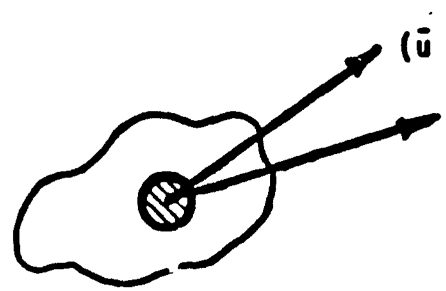
Notes:

I. Correct limit for infinitely small particles.

II. Computation of two-phase flow no more complex than for single-phase flow.

DETERMINISTIC SEPARATED FLOW (DSF) MODEL

ASSUMPTION: FINITE INTERPHASE TRANSPORT RATES BUT PARTICLES ONLY RESPOND TO MEAN MOTION.



NOTES:

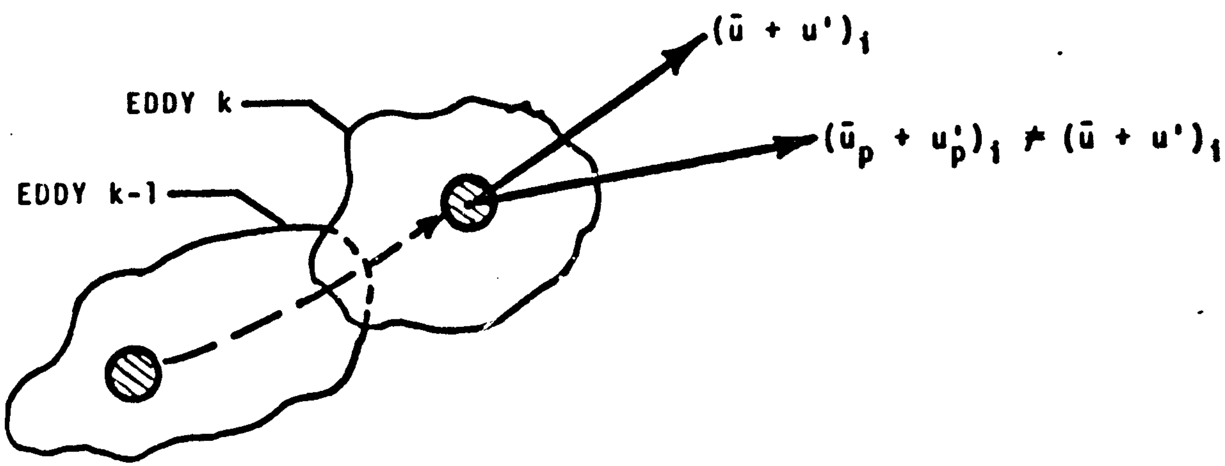
I. PARTICLE DISPERSION IGNORED--ONLY VALID FOR "LARGE" PARTICLES.

II. MOST WIDELY USED APPROXIMATION IN CURRENT MODELS OF COMBUSTING SPRAYS AND PULVERIZED COAL.

III. FLOW FIELD FOUND FROM EULERIAN CALCULATION WITH DISTRIBUTED SOURCE TERMS DUE TO PARTICLES. LAGRANGIAN CALCULATION DETERMINES PARTICLE TRAJECTORIES.

STOCHASTIC SEPARATED FLOW (SSF) MODEL

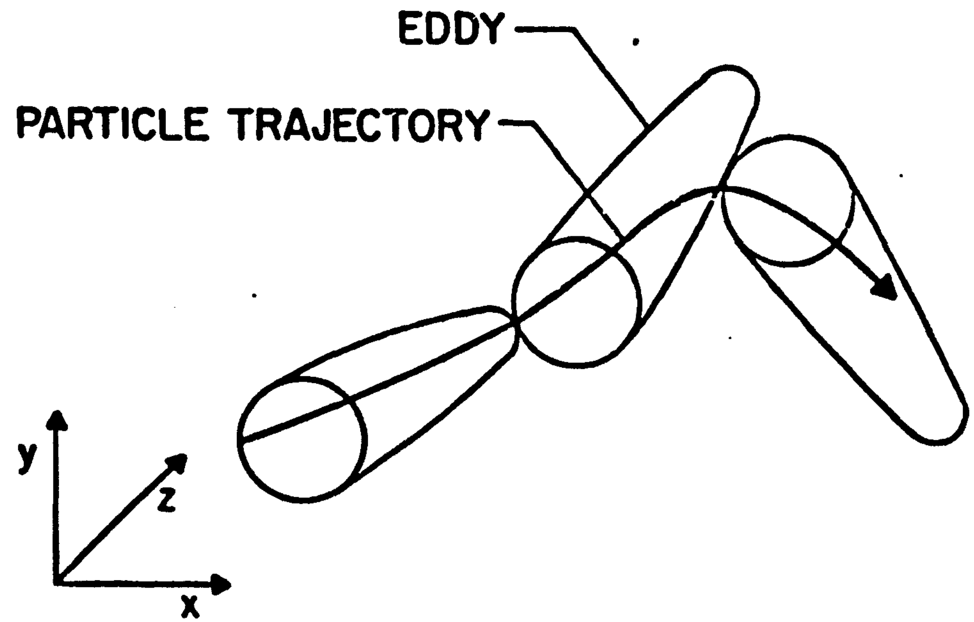
ASSUMPTION: FINITE INTERPHASE TRANSPORT RATES WITH PARTICLES INTERACTING WITH INDIVIDUAL EDDIES WHOSE PROPERTIES ARE FOUND BY RANDOM SAMPLING OF LOCAL TURBULENCE PROPERTIES.



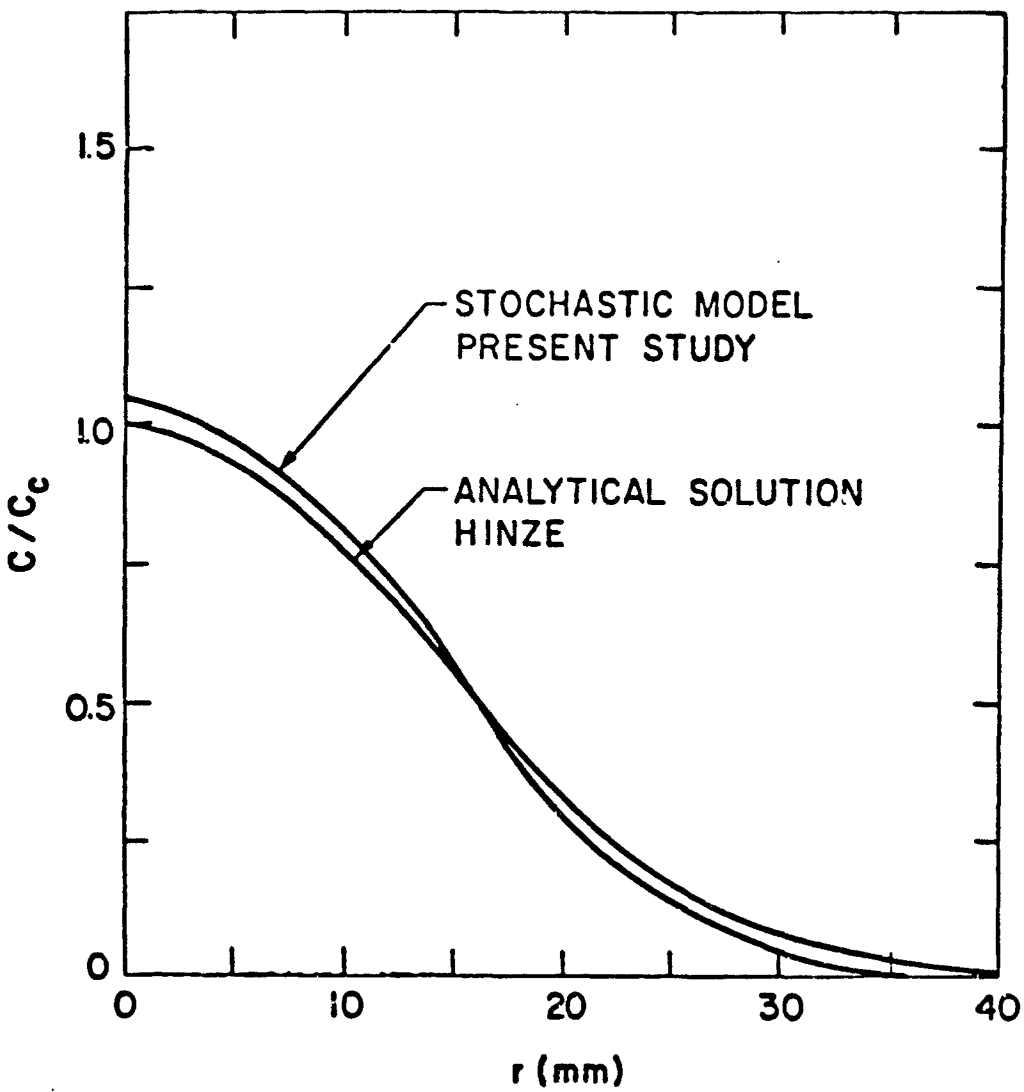
NOTES:

I. INVOLVES ADDITIONAL ASSUMPTIONS CONCERNING THE PROPERTIES, SIZE AND LIFETIME OF EDDIES.

II. COMPUTATIONS SIMILAR TO DSF MODELS, BUT MONTE CARLO TECHNIQUES USED TO FIND STATISTICALLY SIGNIFICANT NUMBER OF PARTICLE TRAJECTORIES--CAUSING ADDED COMPUTATIONS.



Random-walk particle trajectories for the stachastic method, from Faeth.



Stochastic and analytical predictions of the dispersion of infinitely-small particles, from Faeth.

STRUCTURE OF DILUTE DISPERSED FLOWS

PARTICLE-LADEN JETS

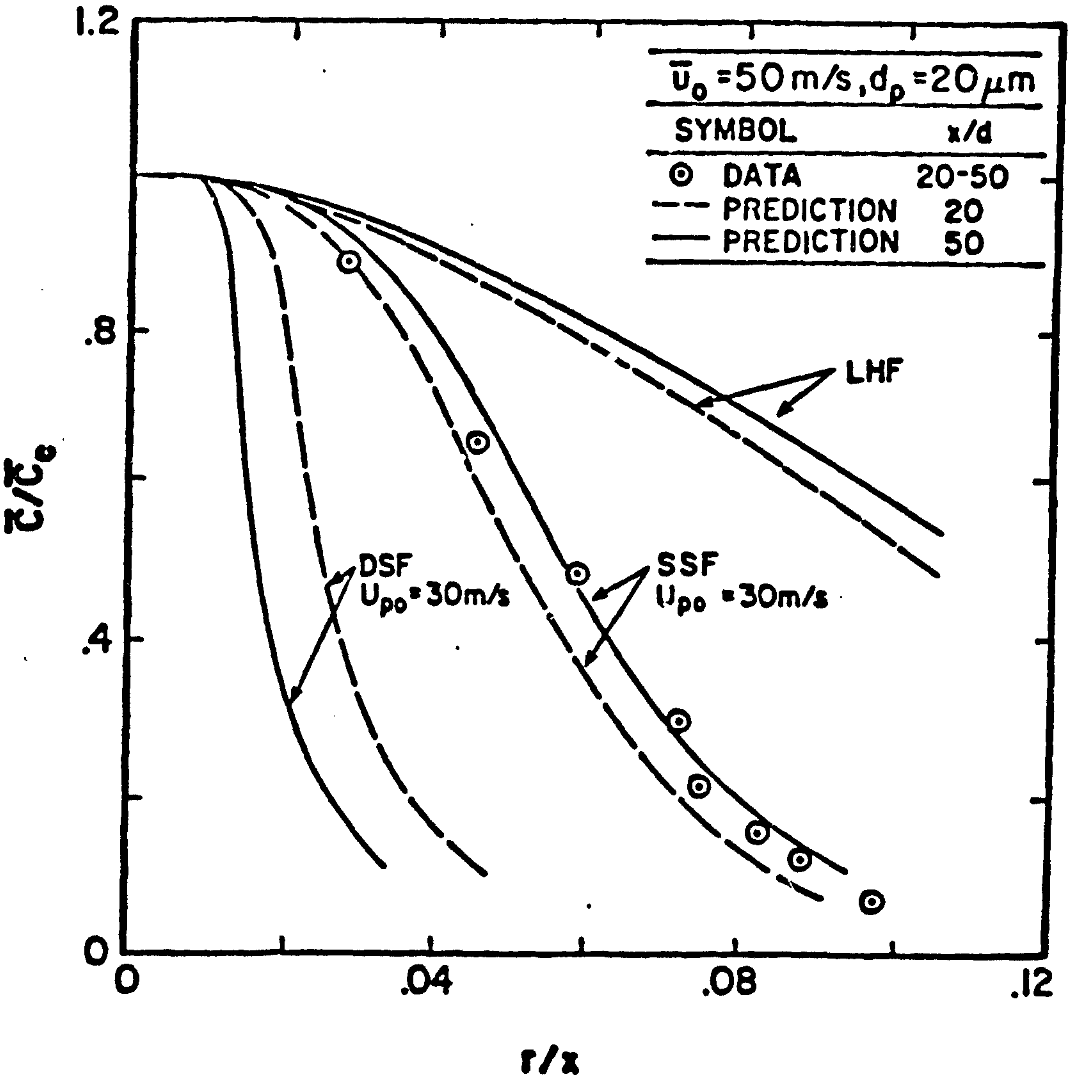
BUBBLY JETS

NON-EVAPORATING SPRAYS

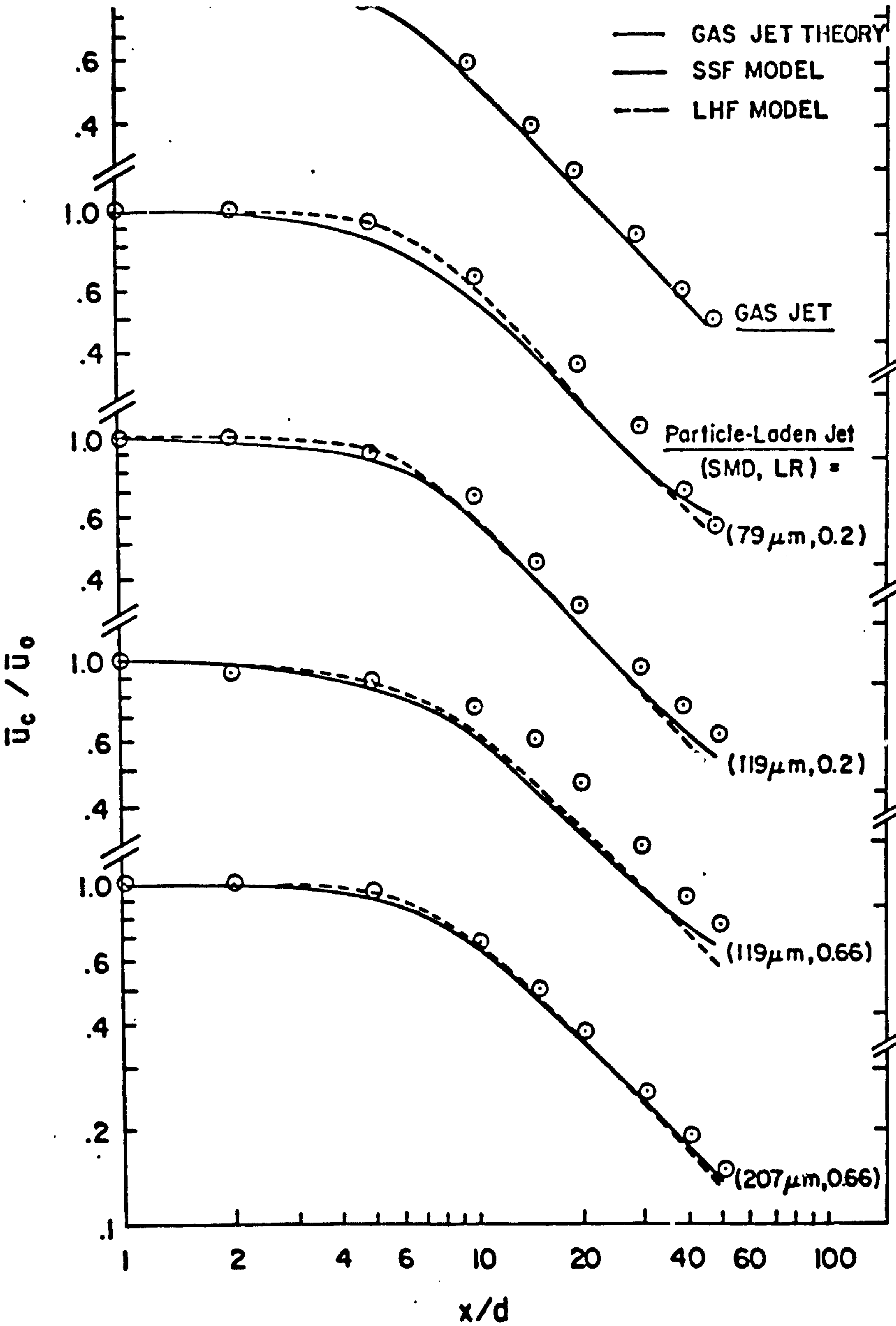
EVAPORATING SPRAYS

COMBUSTING SPRAYS

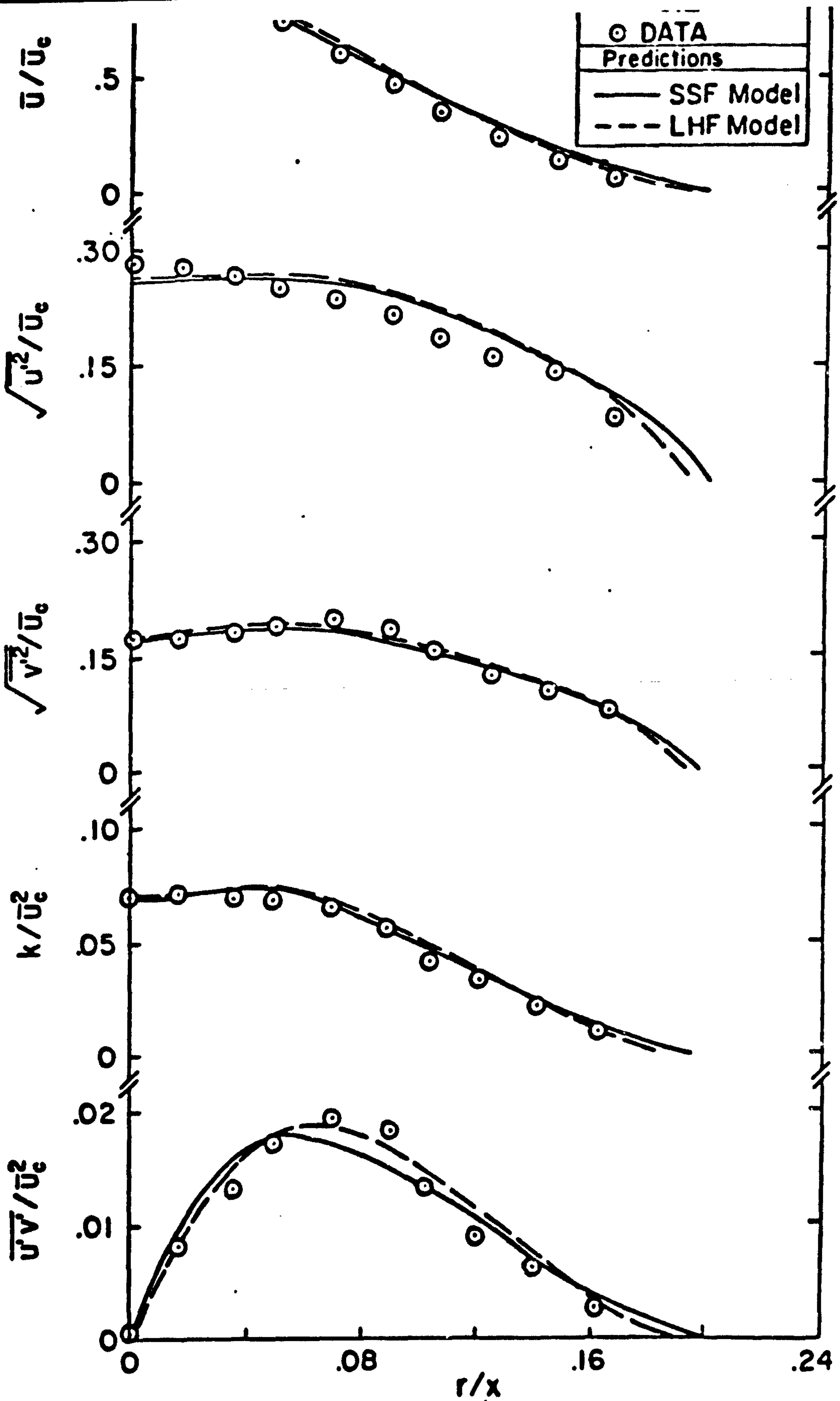
PARTICLE-LADEN JETS



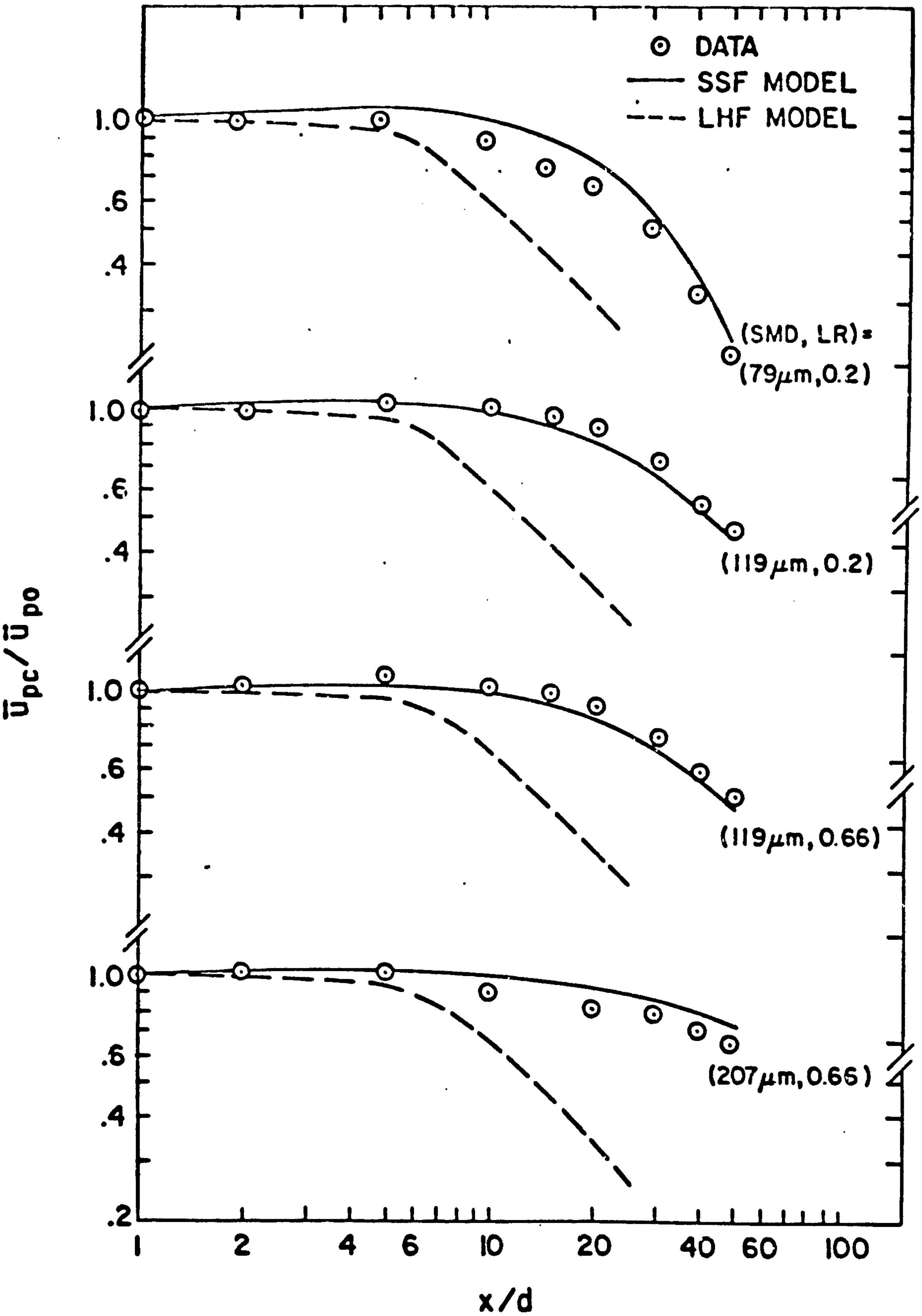
Particle concentrations in a particle-laden jet, from Shuen et al.



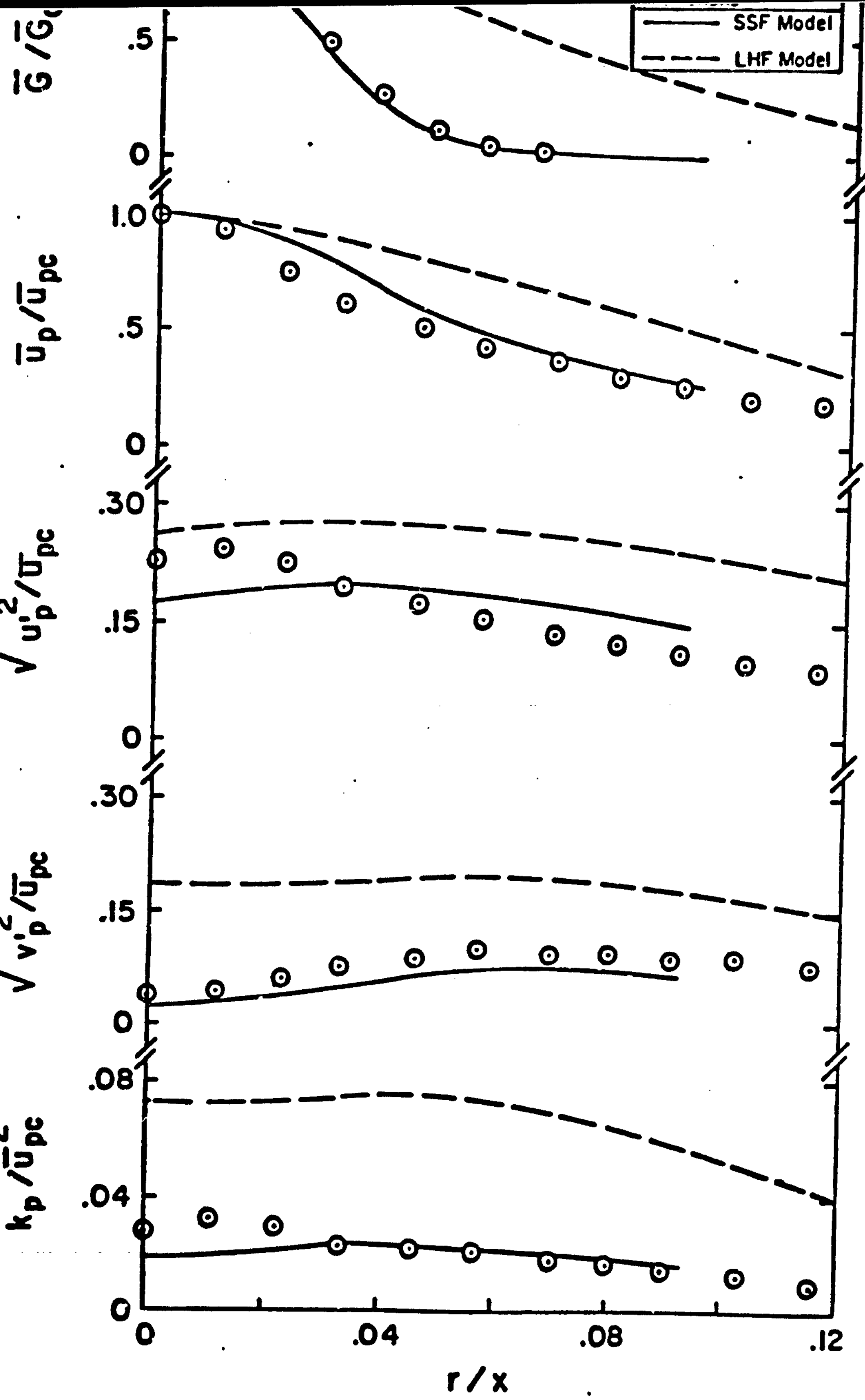
Continuous-ohase velocities along the axis of particle-laden jets, from Shuen et al.



Continuous-phase velocities in a particle laden jet, from Shuen et al.

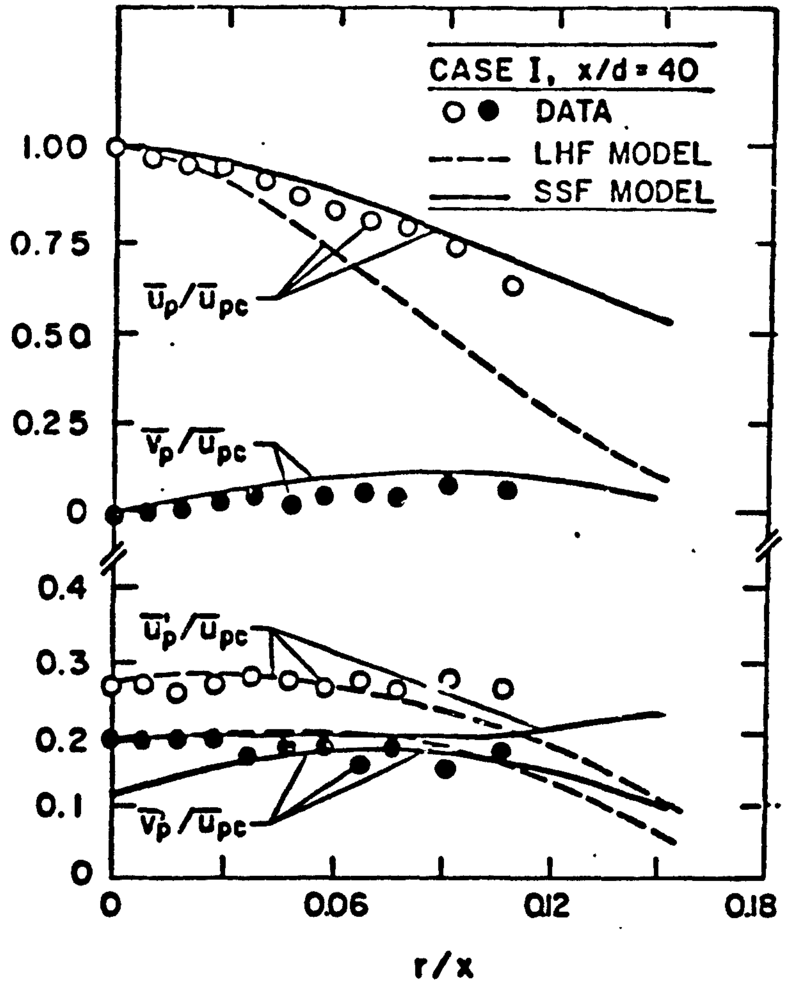


Particle velocities along the axis of particle-laden jets, from Shuen et al.

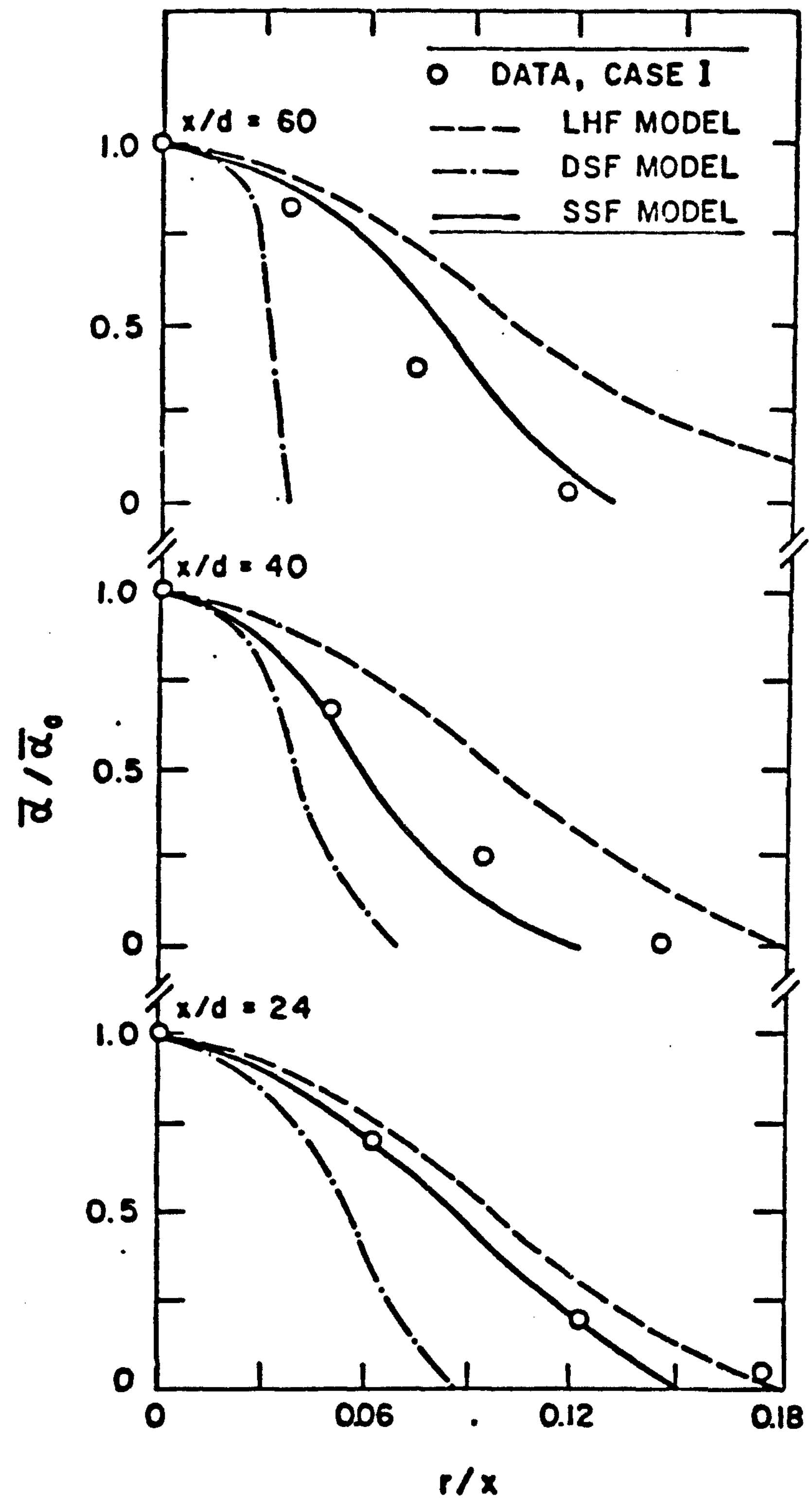


Particle phase velocities in a particle-laden jet, from Shuen et al.

BUBBLY JETS

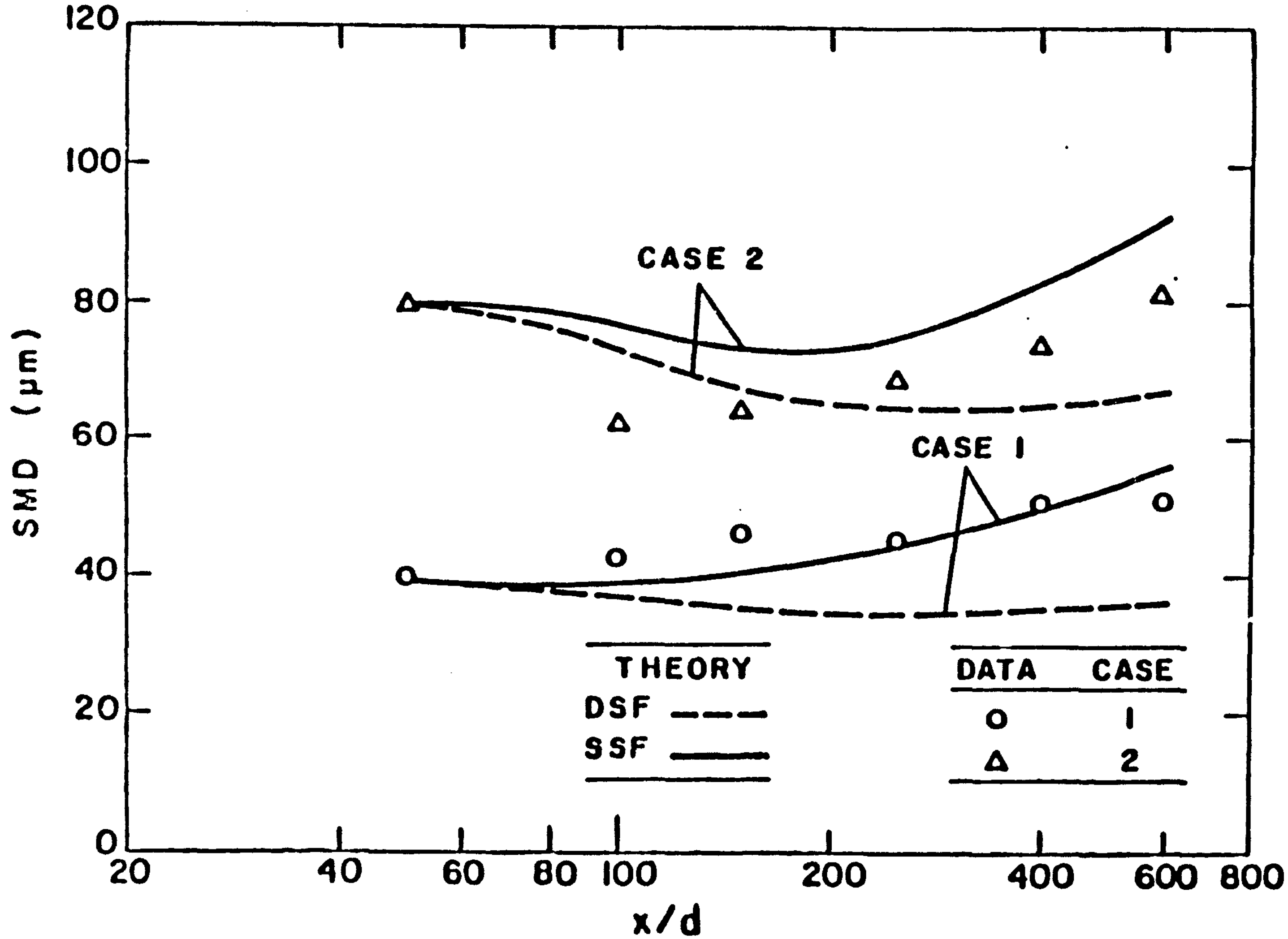


Bubble phase velocities in bubbly jets, from Sun and Faeth.

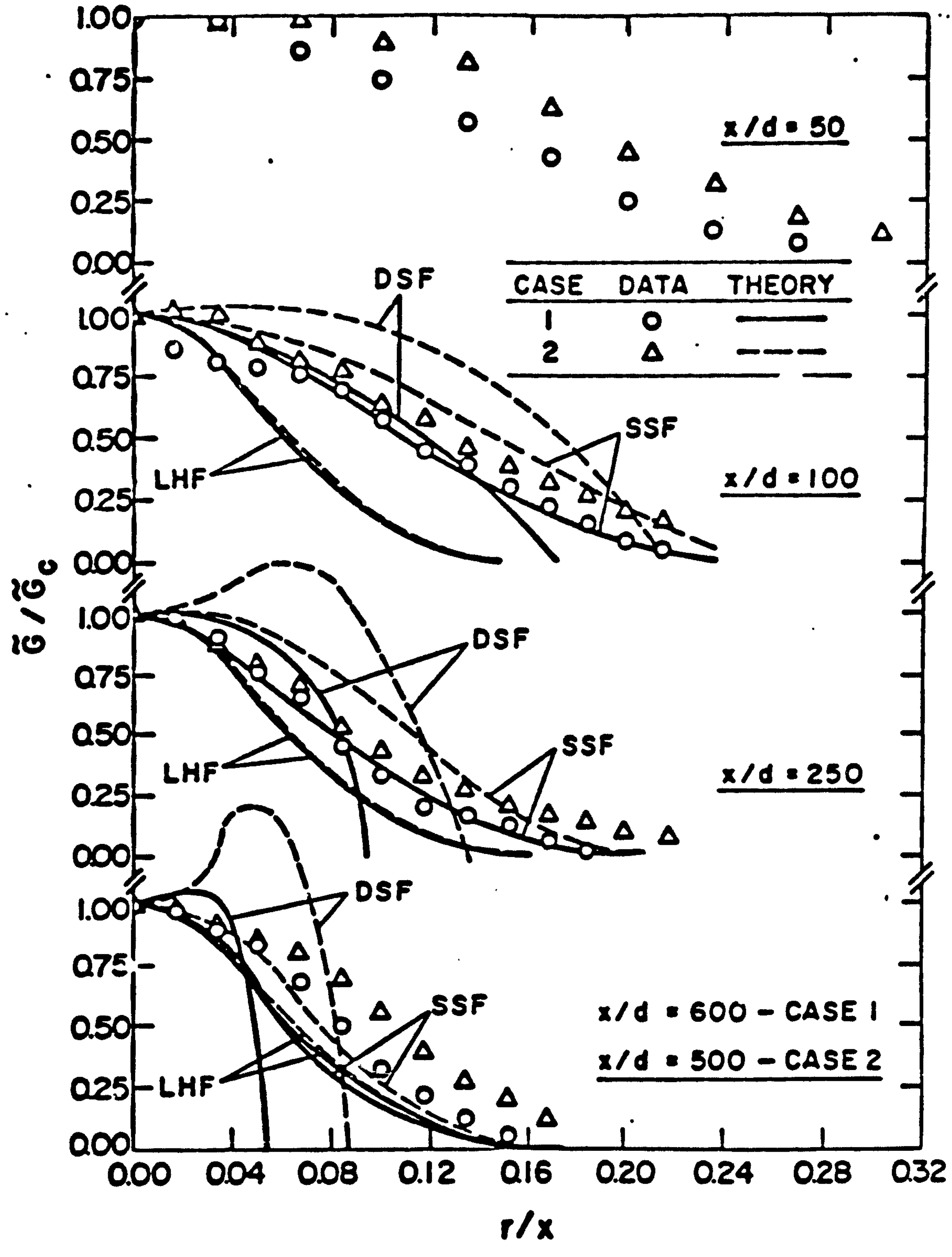


Bubble number intensity distributions in bubbly jets, from Sun and Faeth.

NONEVAPORATING SPRAYS

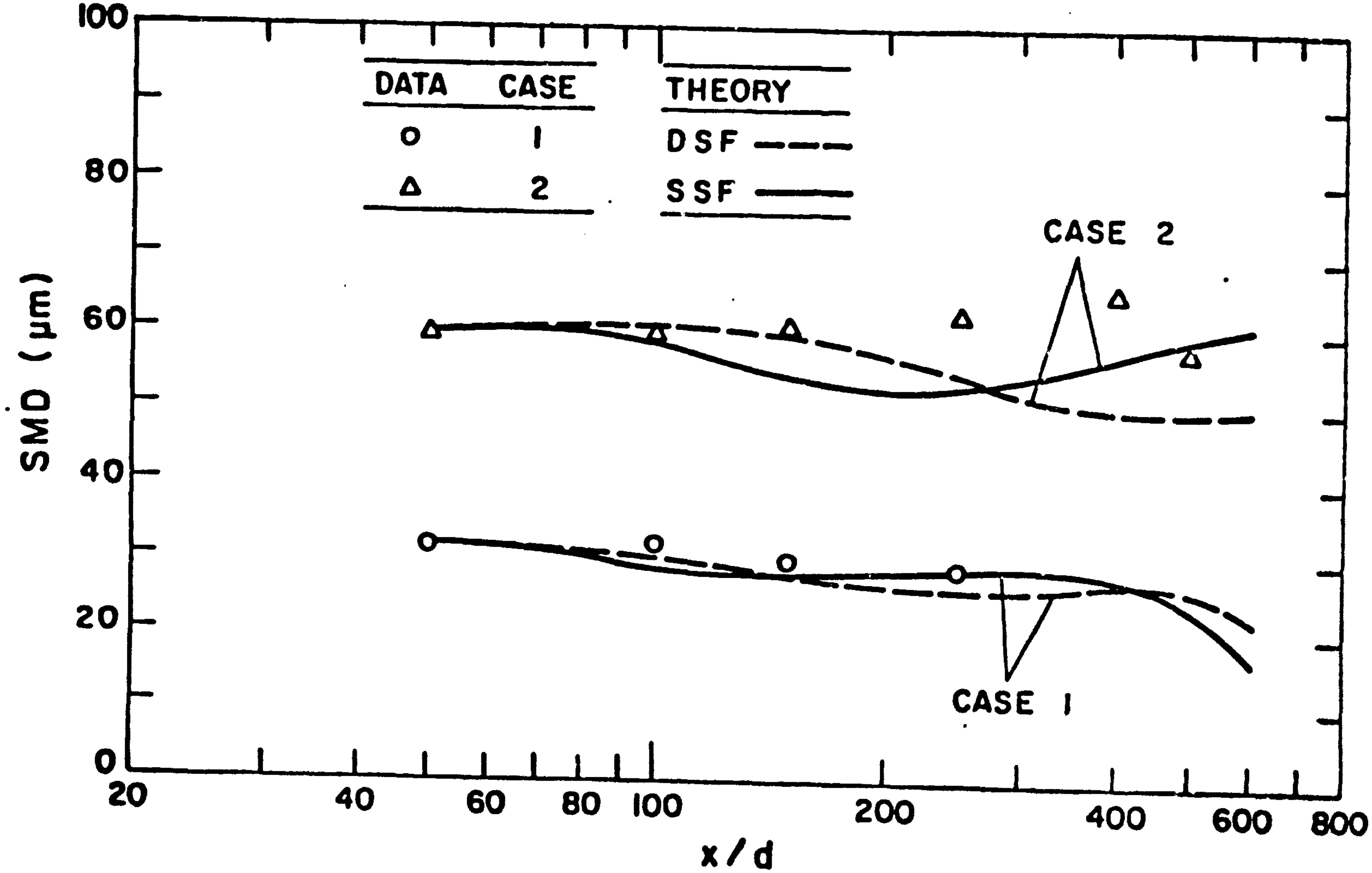


Sauter mean diameter along the axis of nonevaporating sprays, from Solomon et al.

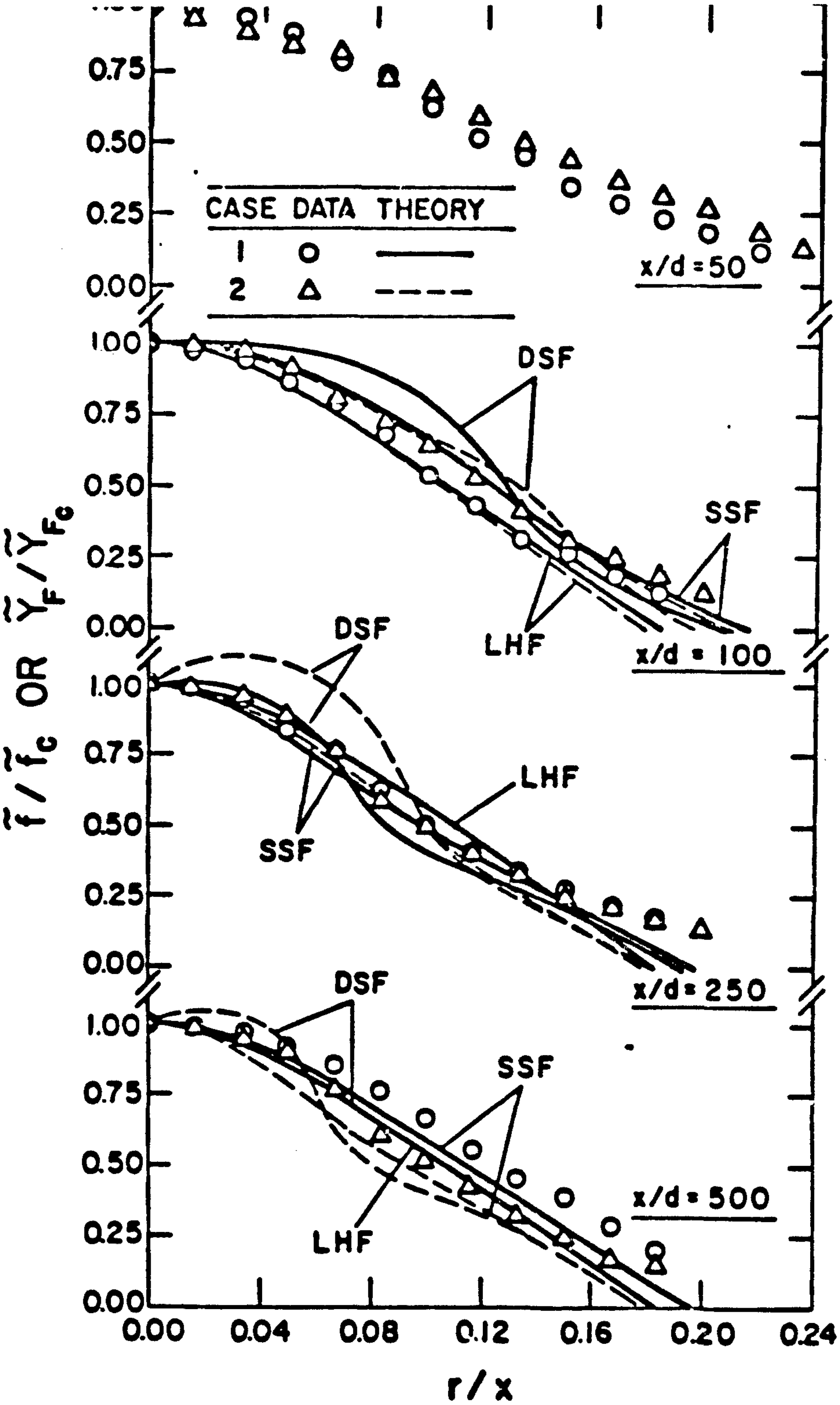


Liquid flux distributions in nonevaporating sprays, from Solomon et al.

Evaporating Sprays



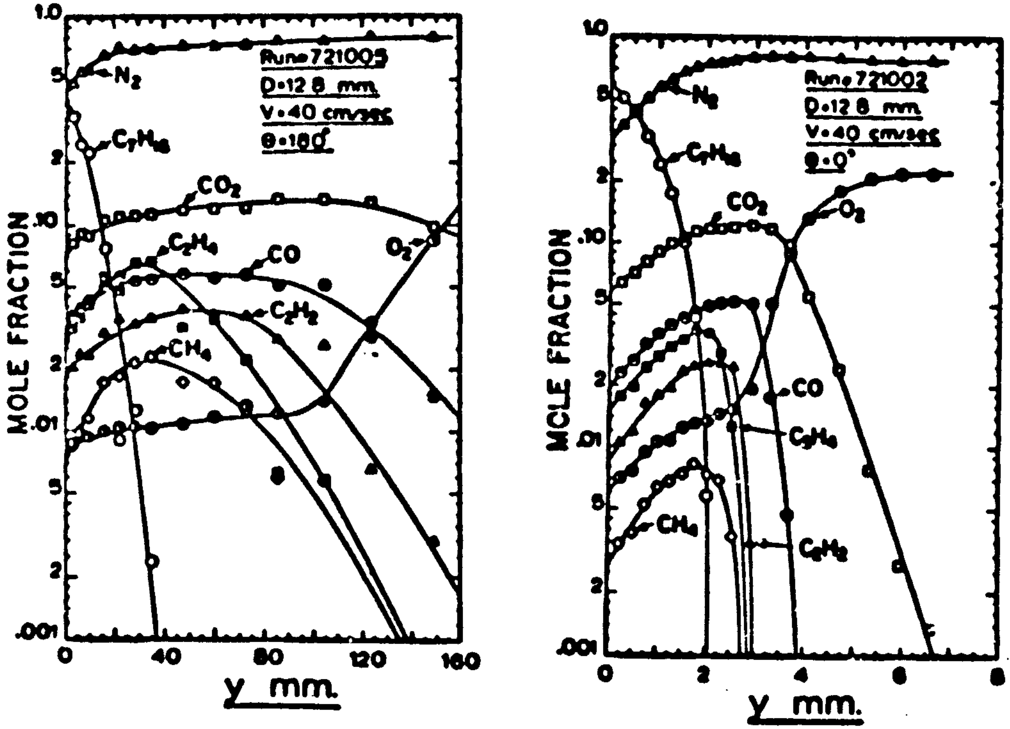
Variation of Sauter mean diameter along the axis of evaporating sprays, from Solomon et al.



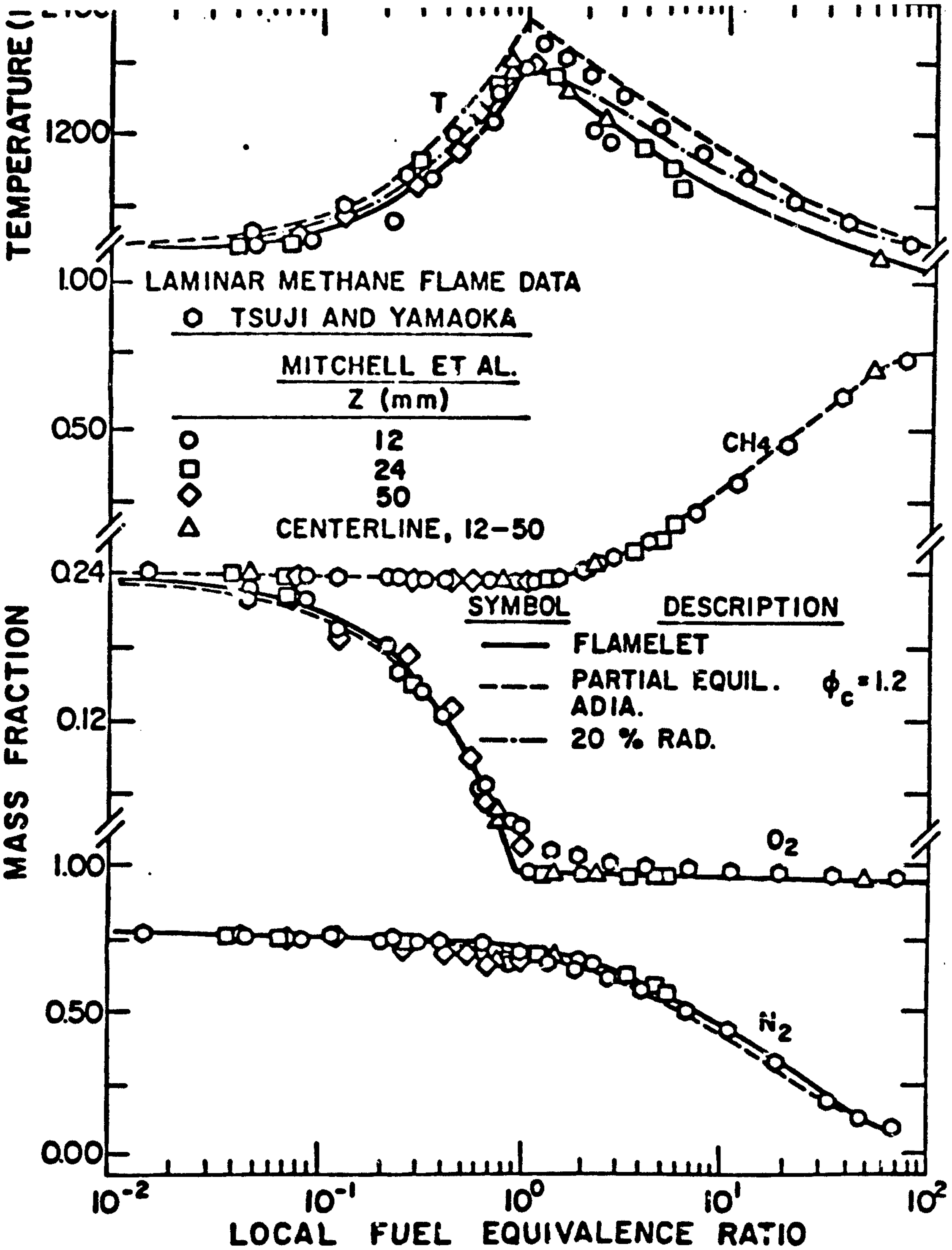
Predicted and measured radial profiles of mean mixture fraction (LHF) or total Freon-11 concentration (SSF).

From Solomon et al.

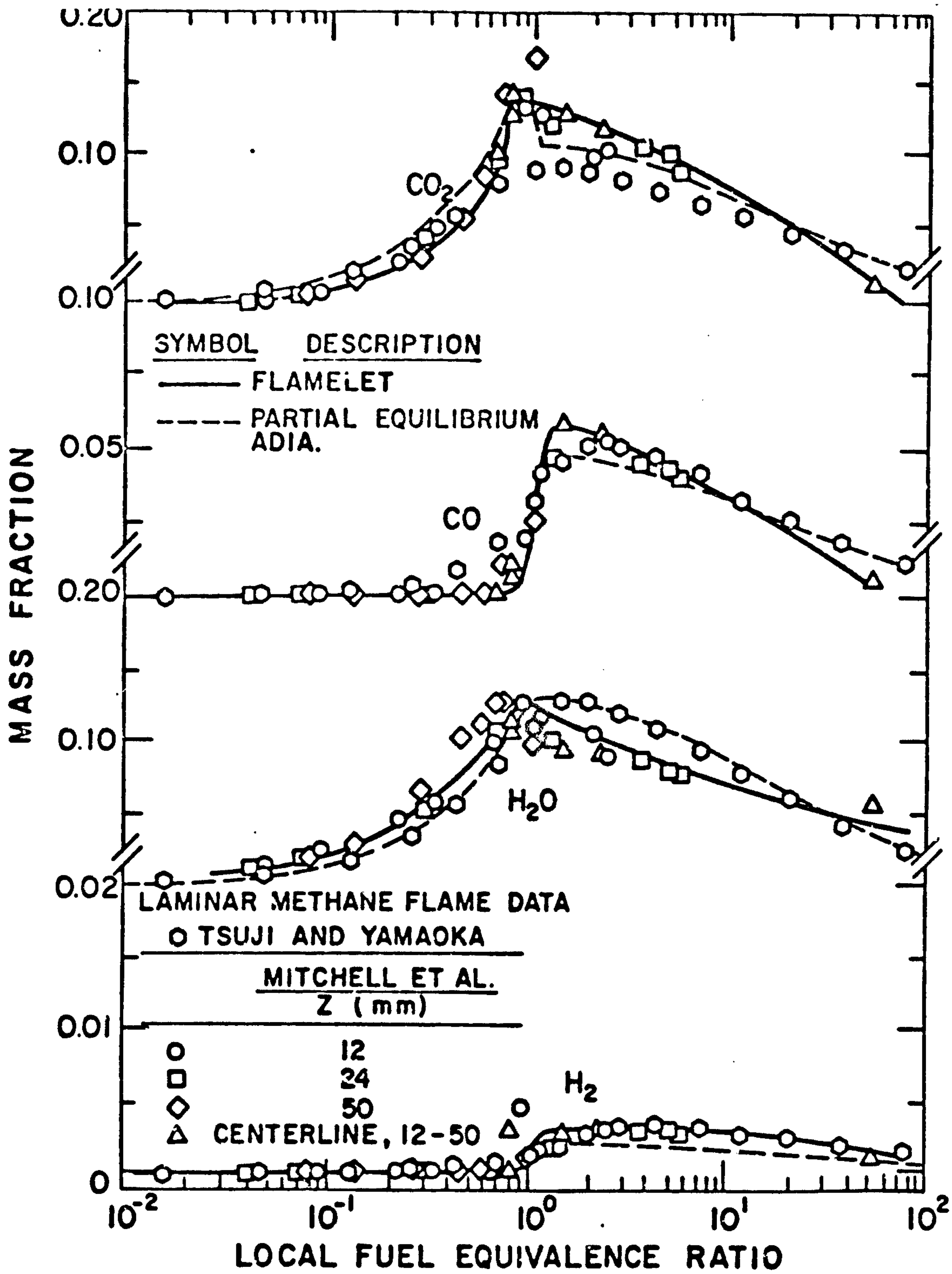
COMBUSTING SPRAYS



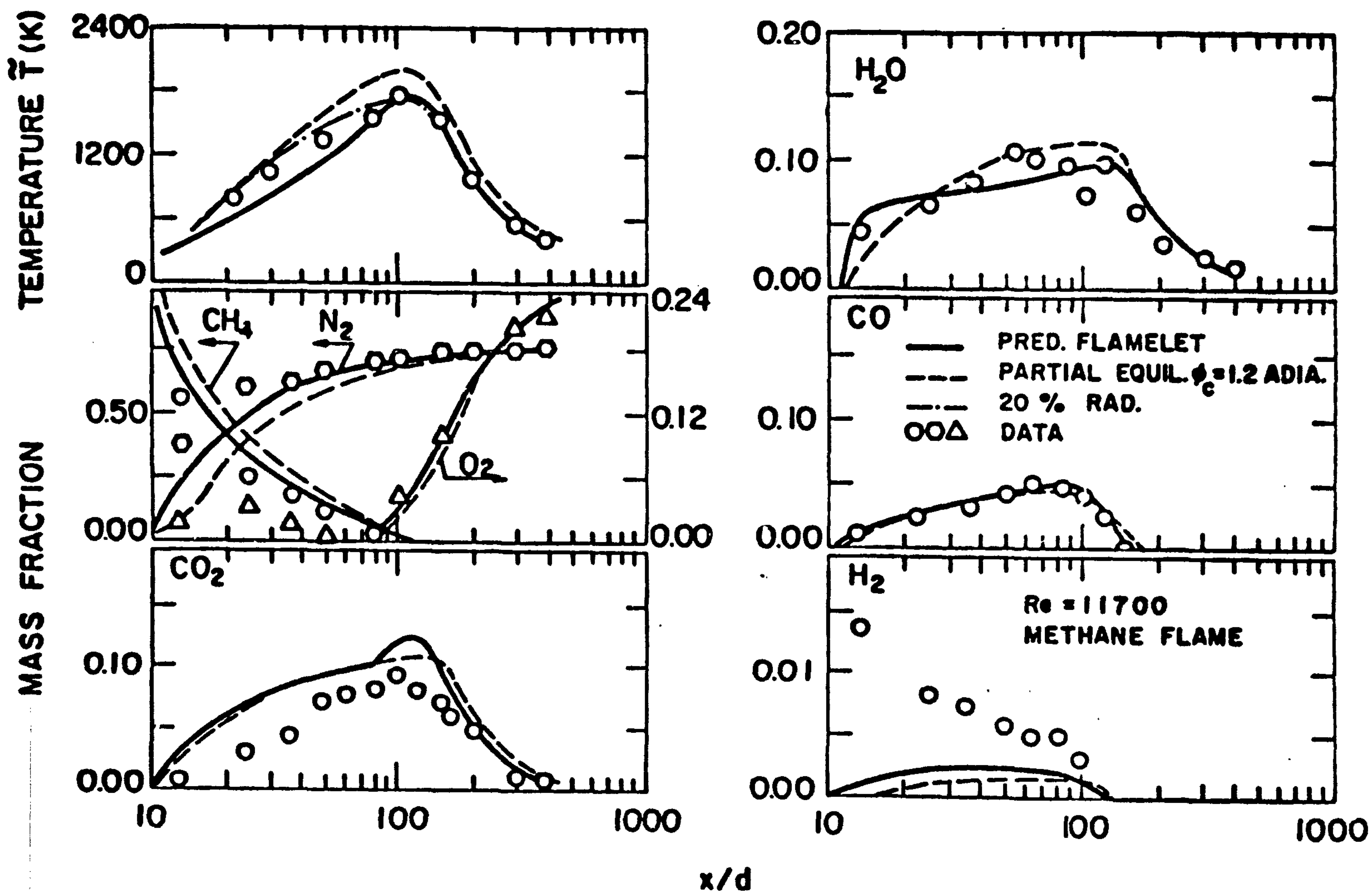
Scalar properties in a laminar n-heptane diffusion flame.



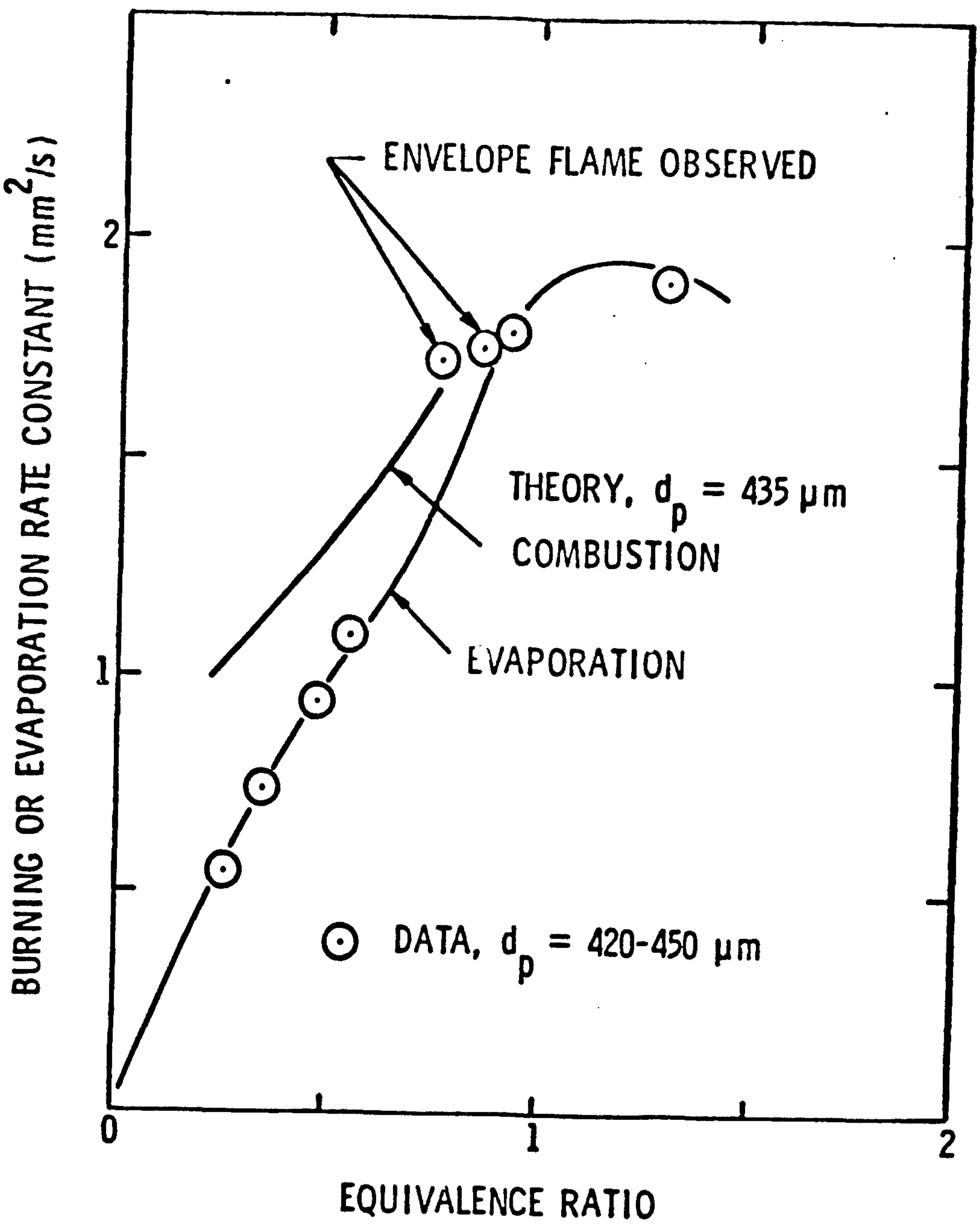
State relationships for methane/air diffusion flames, from Jeng and Faeth.



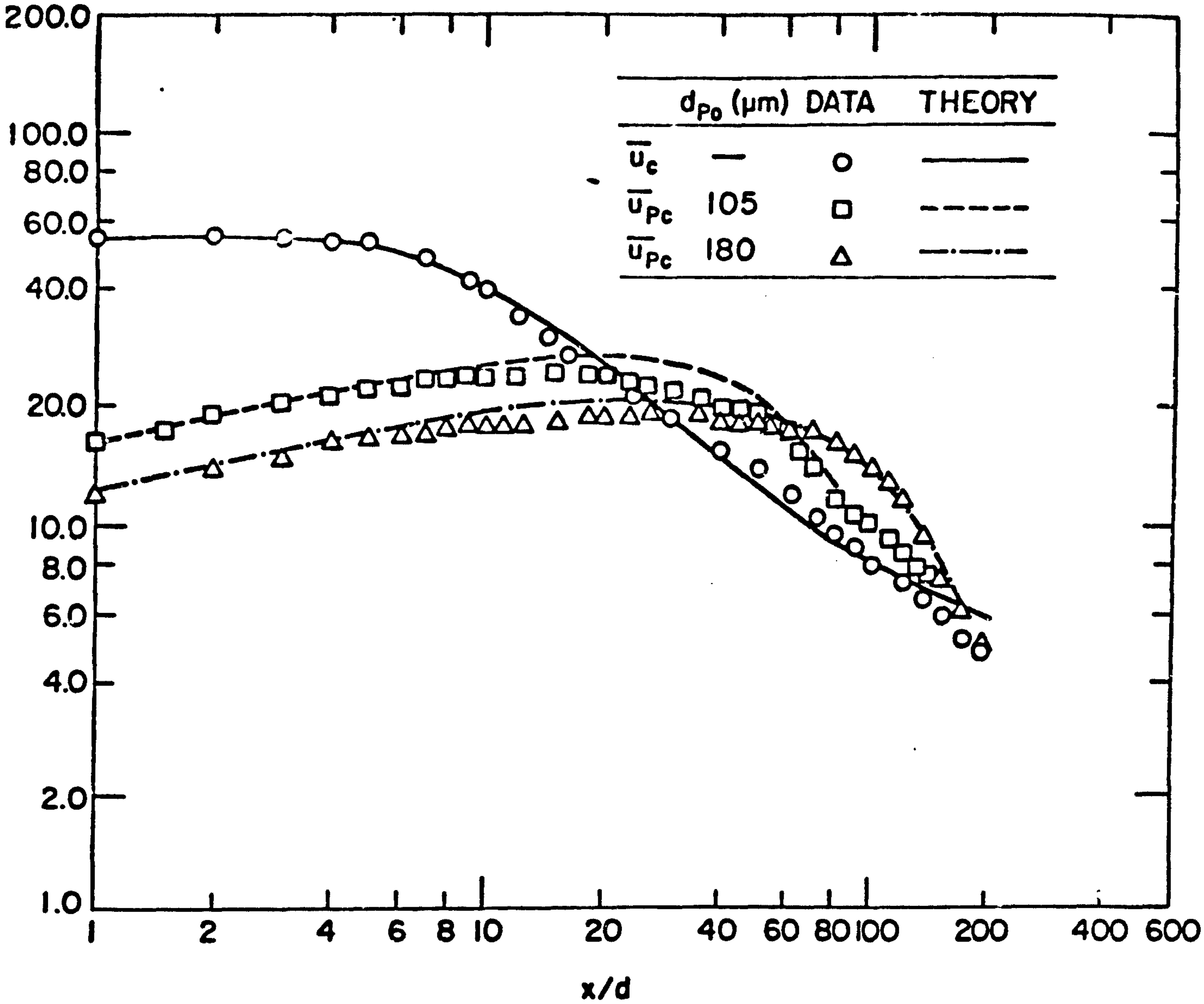
State relationships for methane/air diffusion flames, from Jeng and Faeth.



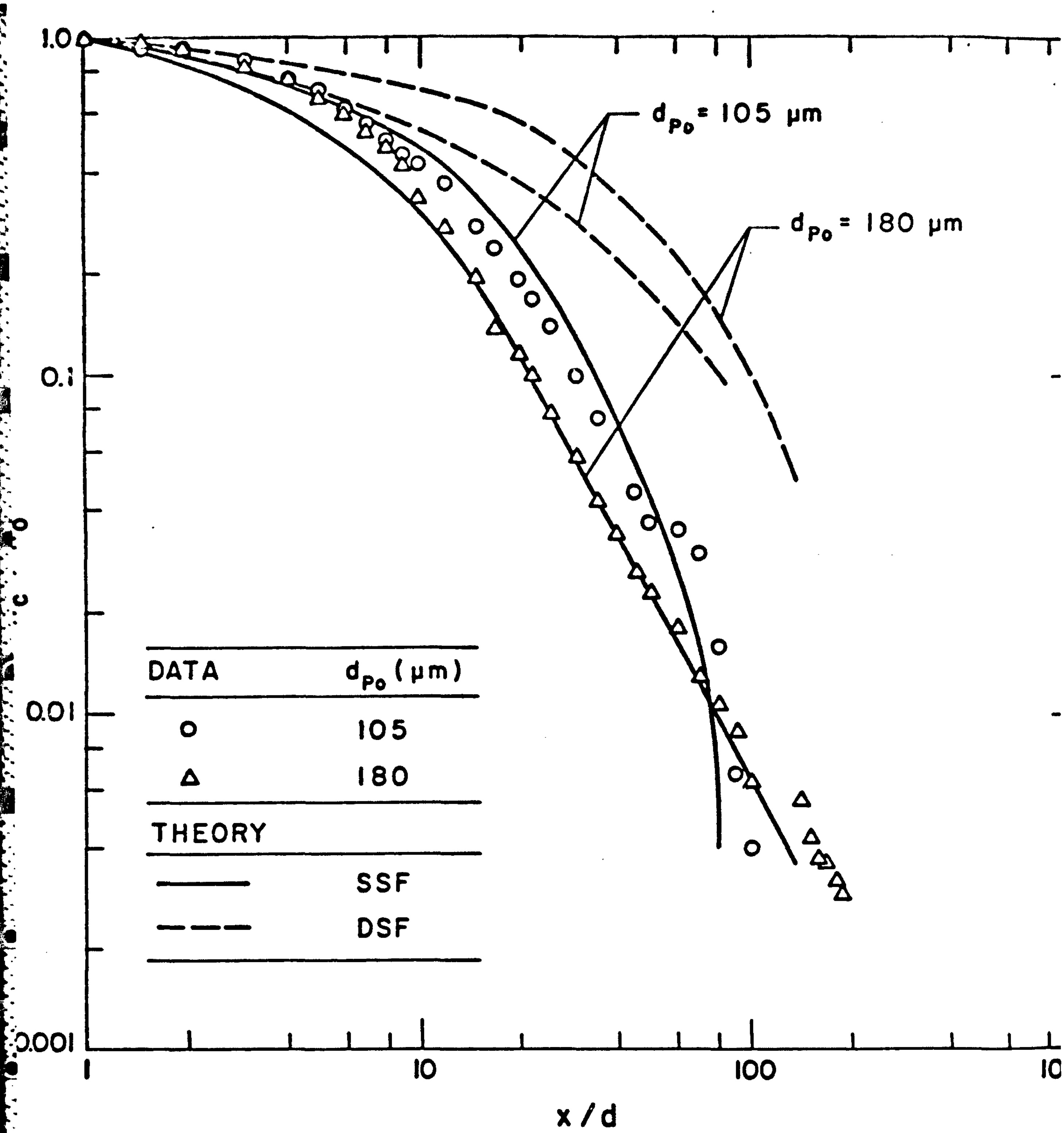
Scalar properties along the axis of a turbulent diffusion flame, from Jeng and Faeth.



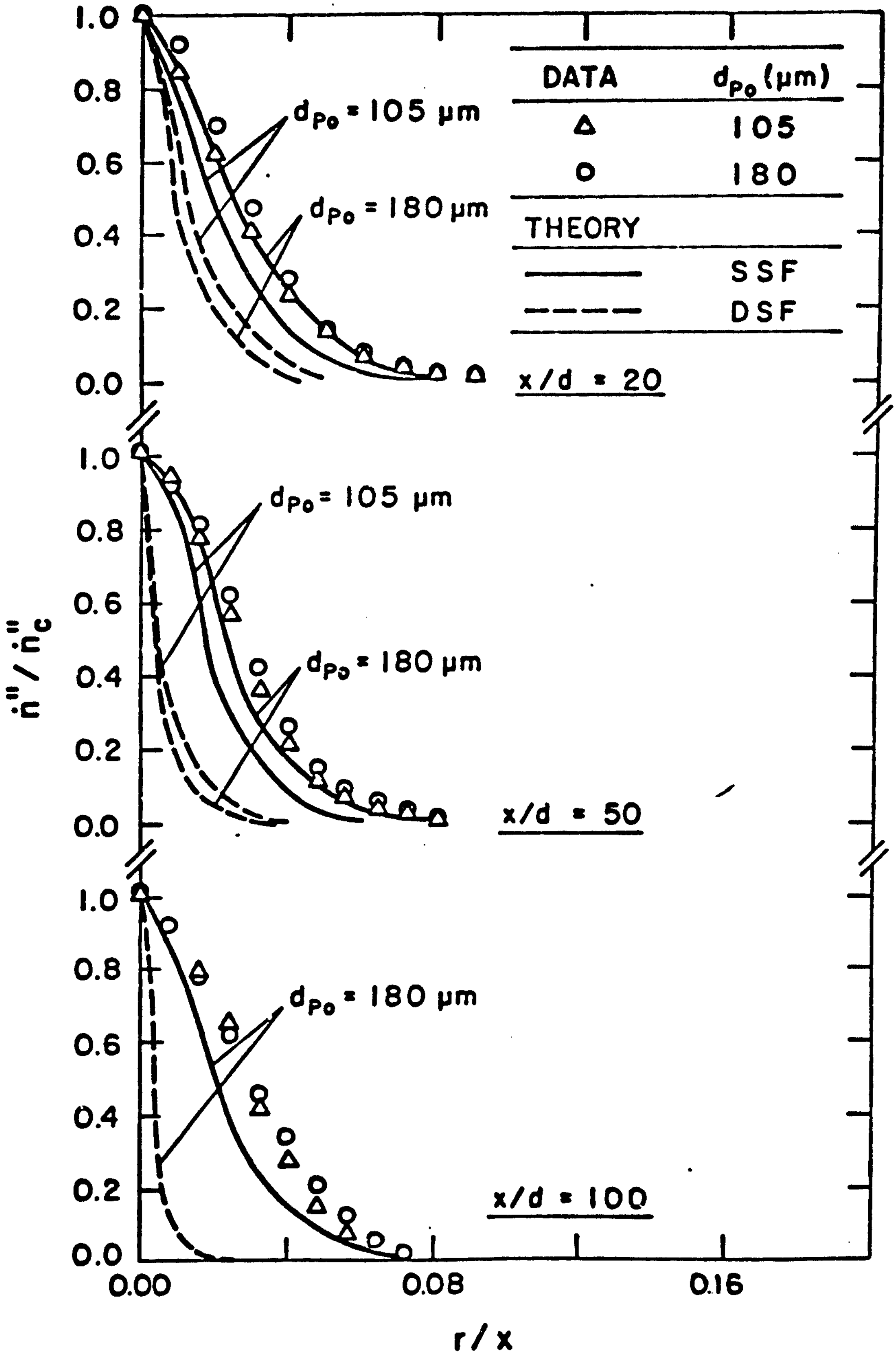
Drop gasification rates for a turbulent flame environment, f~om Szekely and Faeth.



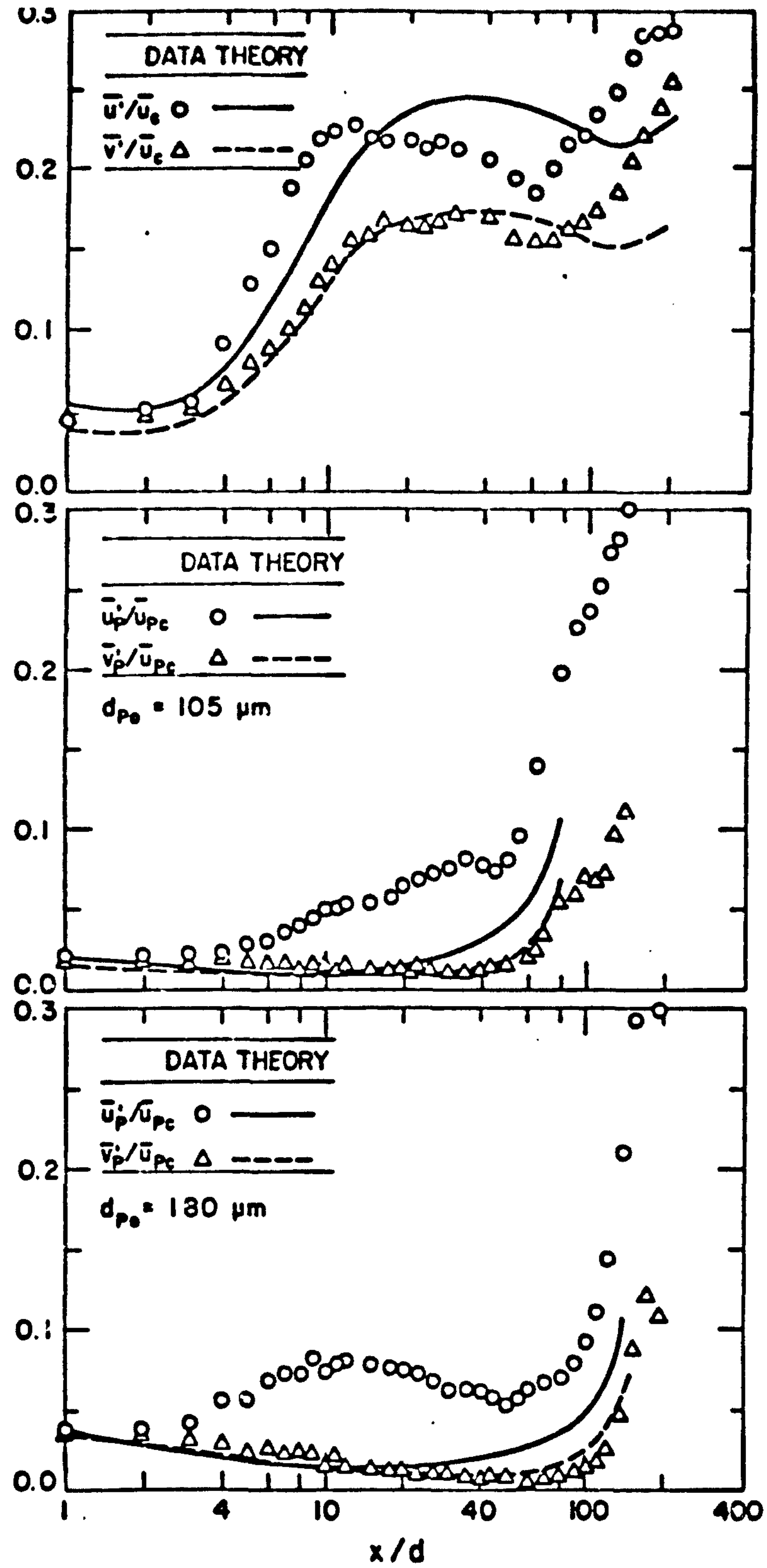
Phase velocities along the .xis of dilute combusting sprays, from Shuen et al.



Drop number fluxes along the axis of dilute combusting sprays, from Shuen et al.



Drop number flux distributions in a dilute combusting spray, from Shuen et al.

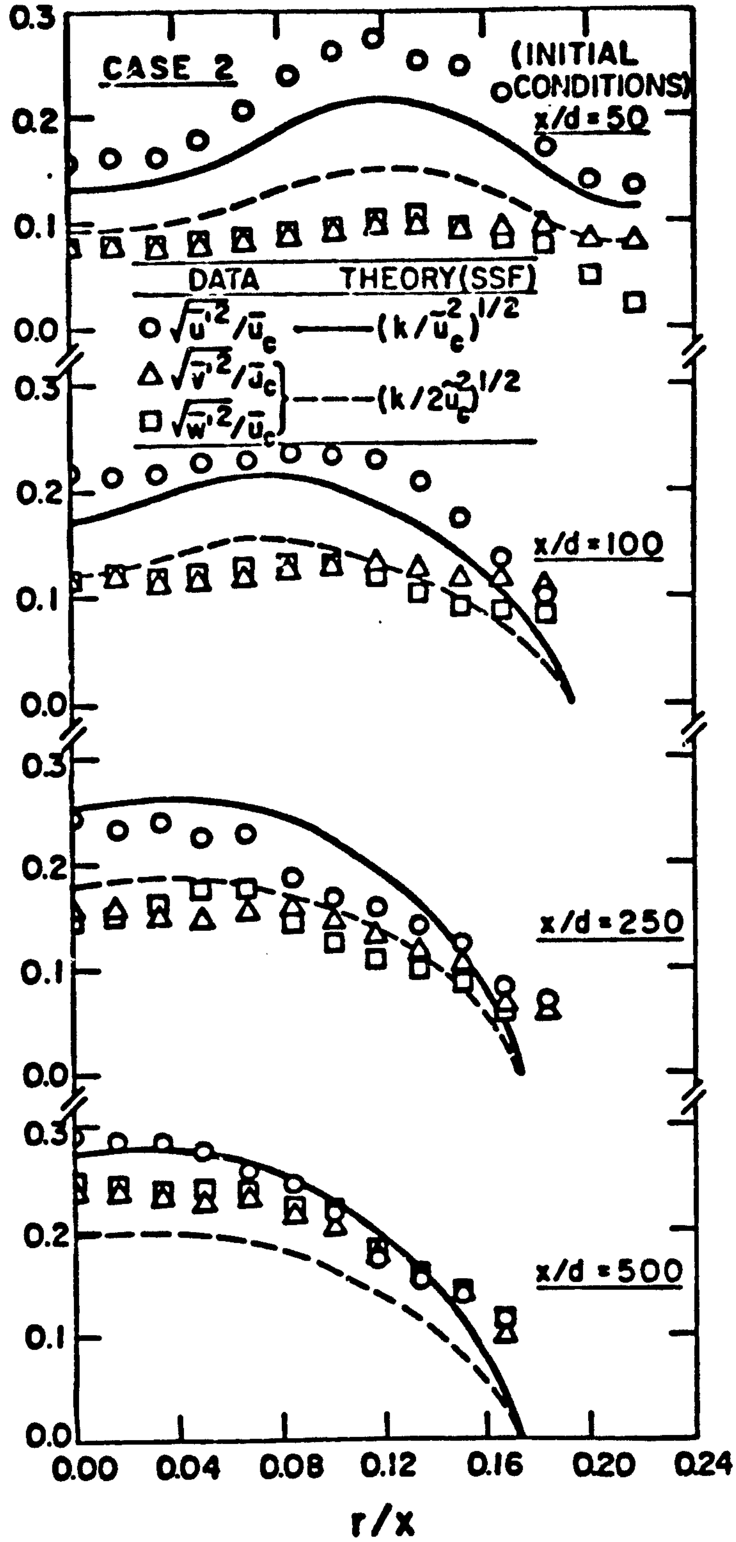


Turbulent fluctuations along the axis of a dilute combusting spray, from Shuen et al.

RESEARCH ISSUES FOR DILUTE SPRAYS

RESEARCH ISSUES FOR DILUTE SPRAYS

- 1. DROP/TURBULENCE INTERACTIONS, E.G., TURBULENT DISPERSION AND MODULATION.



Turbulent fluctuations in a nonevaporating spray, from Solomon et al.

RESEARCH ISSUES FOR DILUTE SPRAYS

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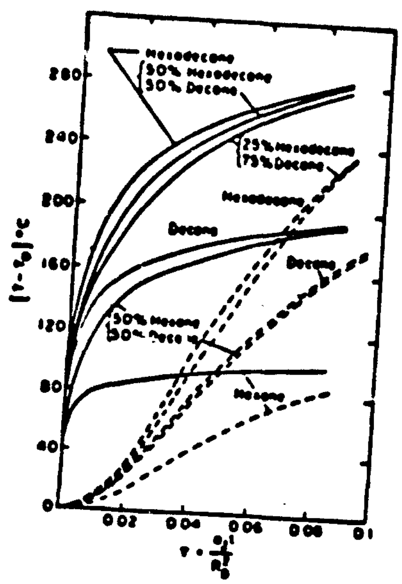
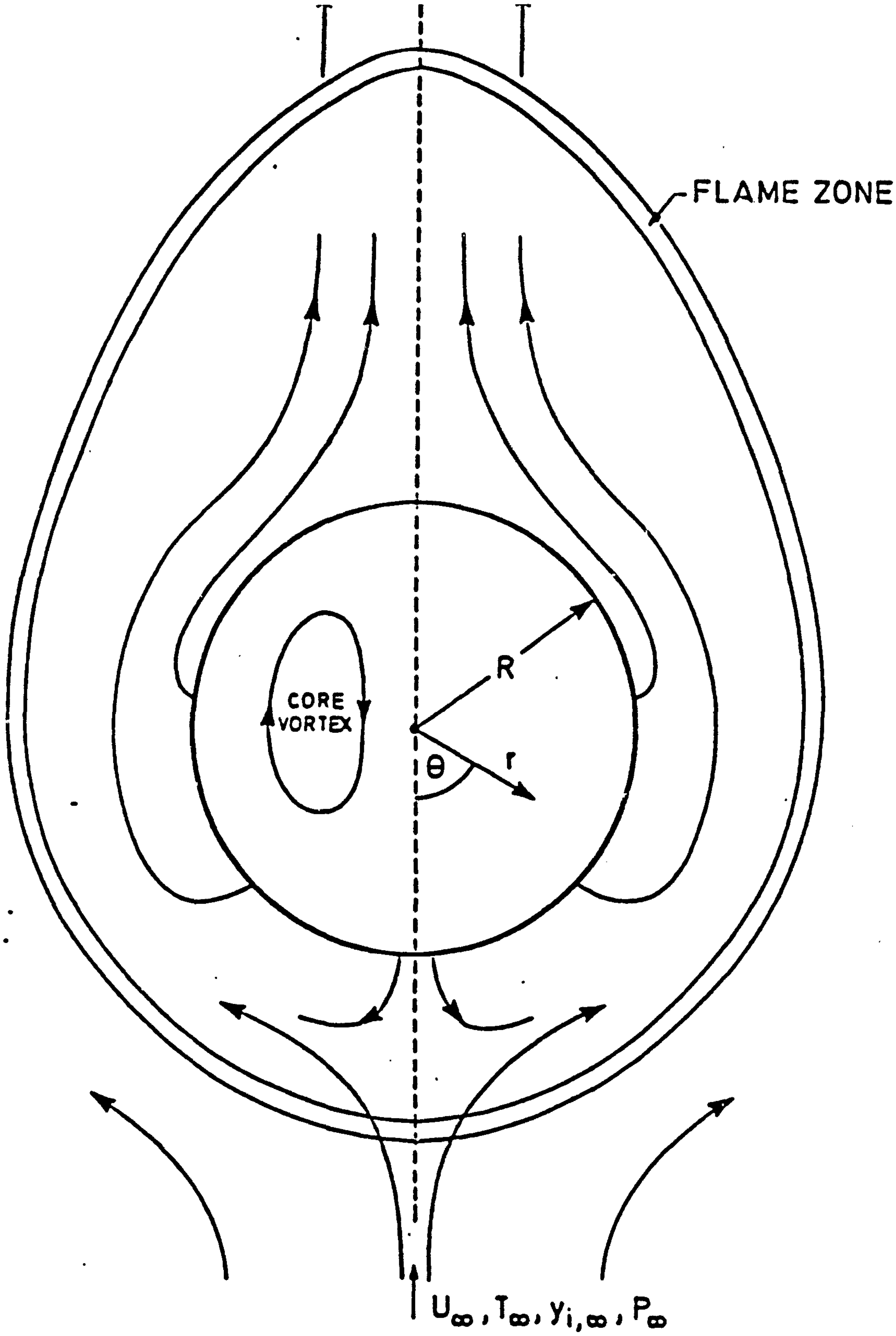
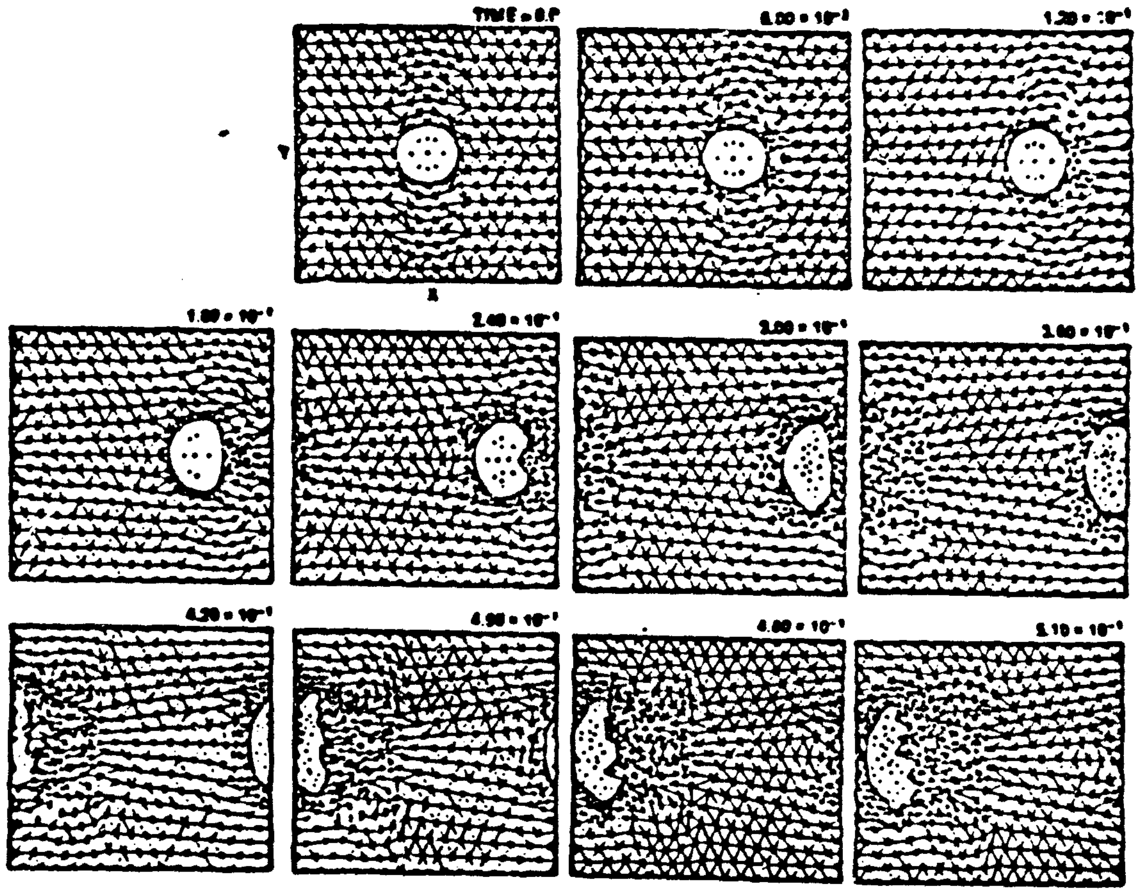
2. INTERPHASE TRANSPORT PHENOMENA, E.G., TRANSIENT AND DEFORMATION EFFECTS, SLURRIES.



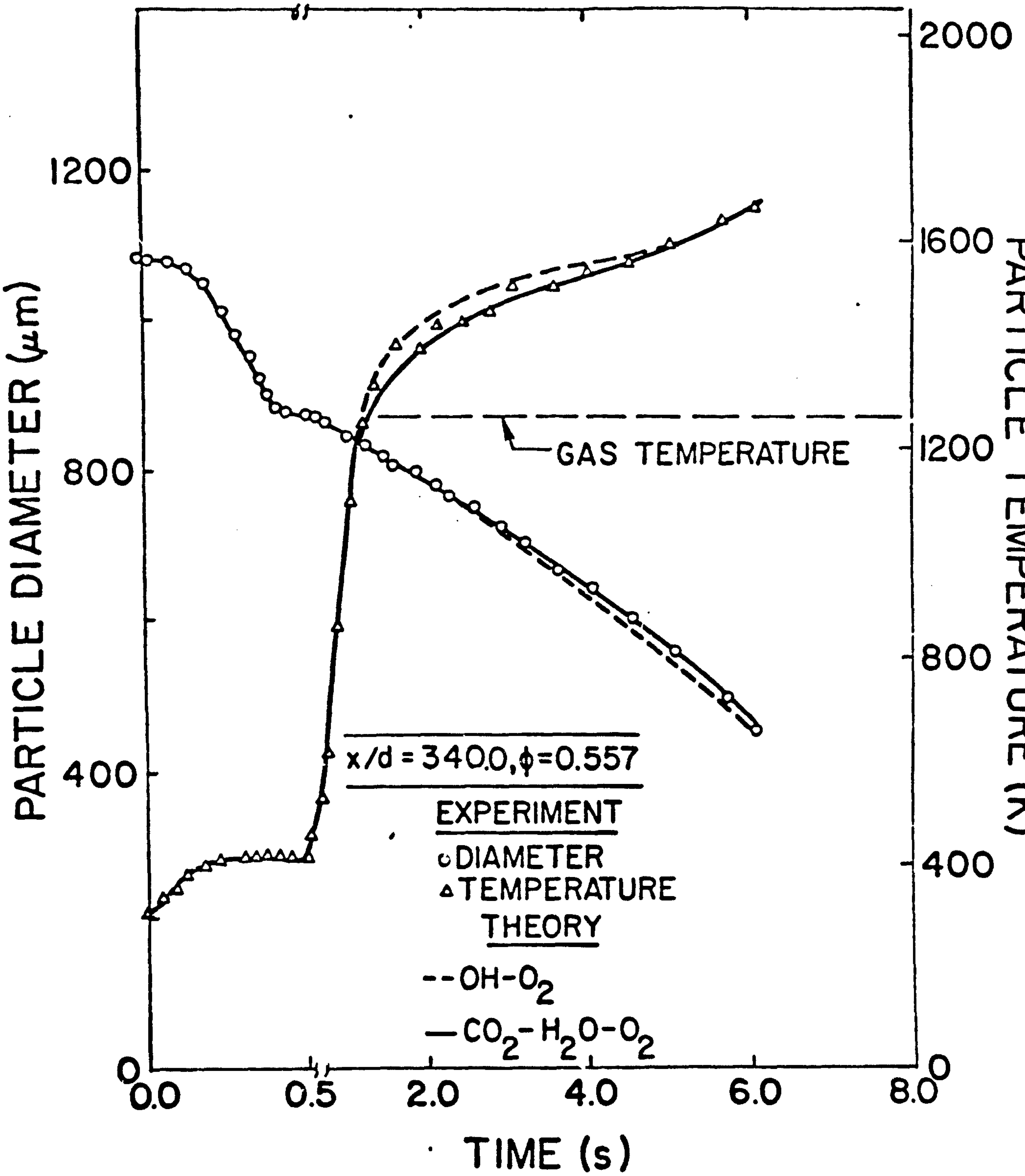
Temperature gradients within a combusting drop.



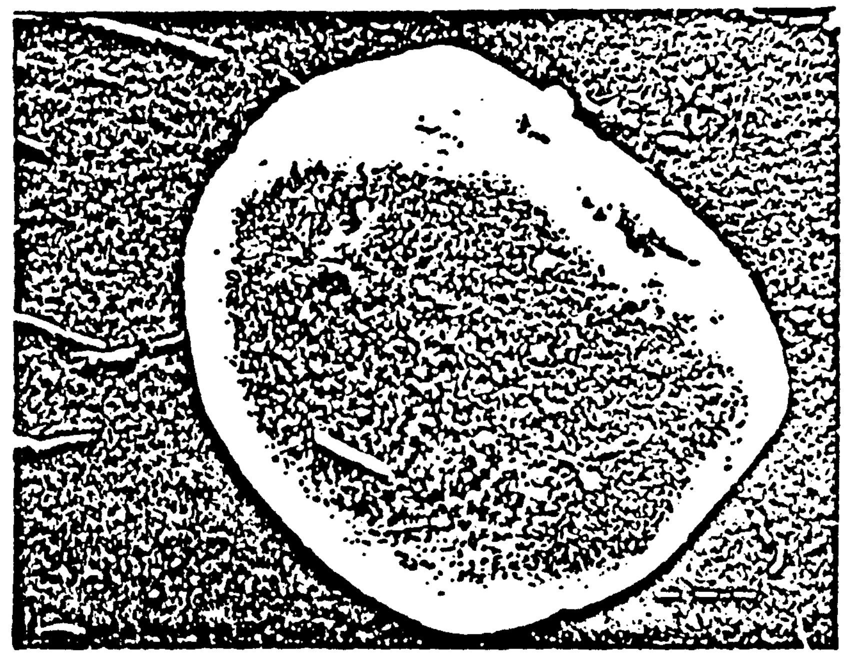
Flow patterns around a combusting drop at low Reynolds number.



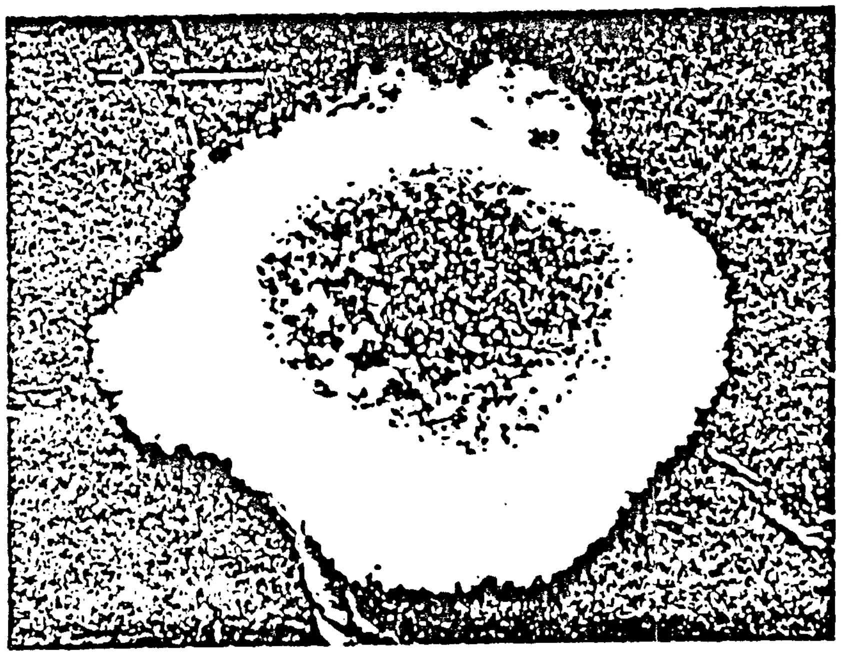
Drop deformation effects showing the need for considering other than spherical shapes, from Oran et al.



Evaluation of slurry-drop-life history predictions for a fuel equivalence ratio of 0.557.



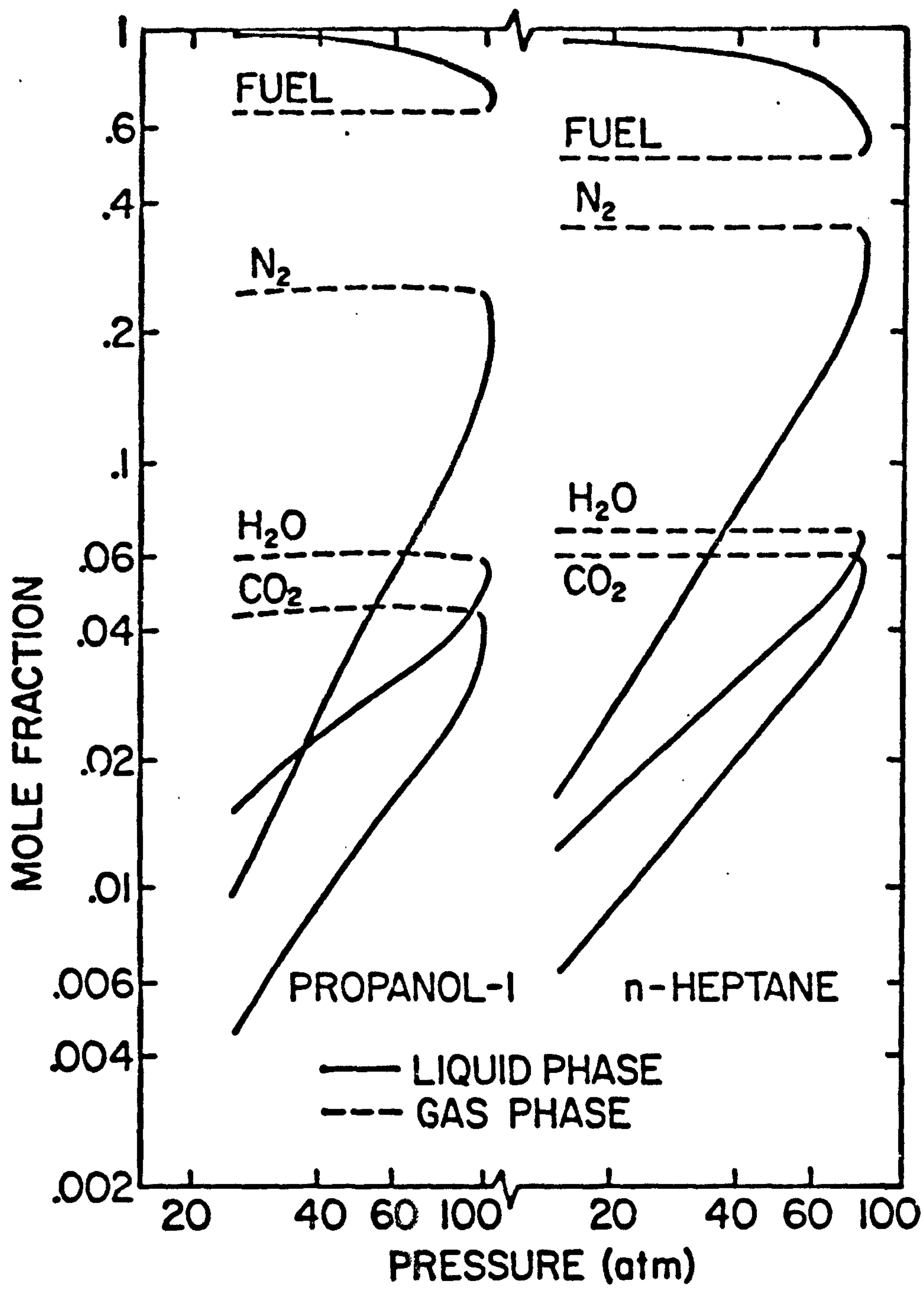
Photograph of an unburned carbon-black
slurry agglomerate (diameter of 73 microns).



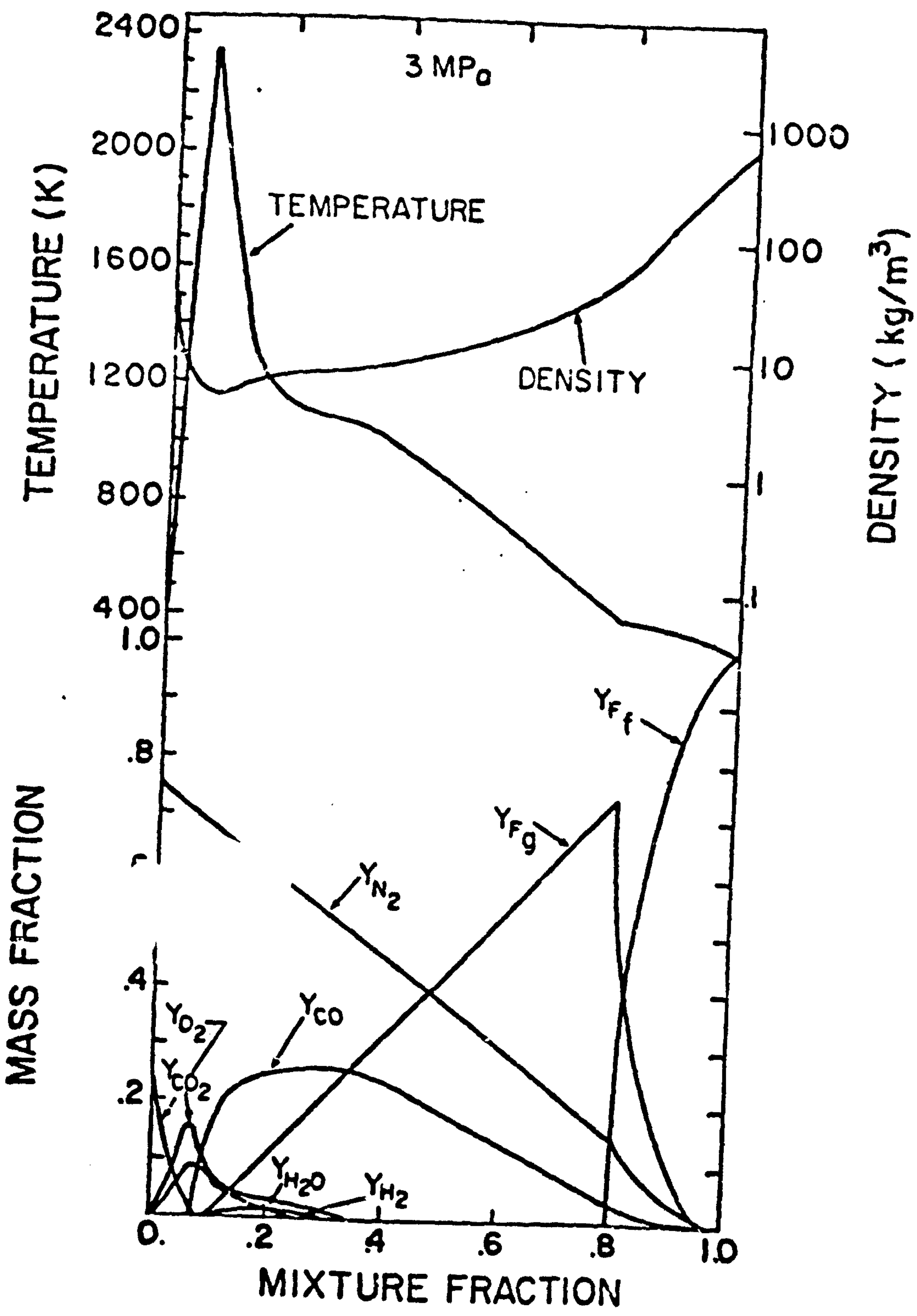
Photograph of a partly burned carbon-black slurry agglomerate.

RESEARCH ISSUES FOR DILUTE SPRAYS

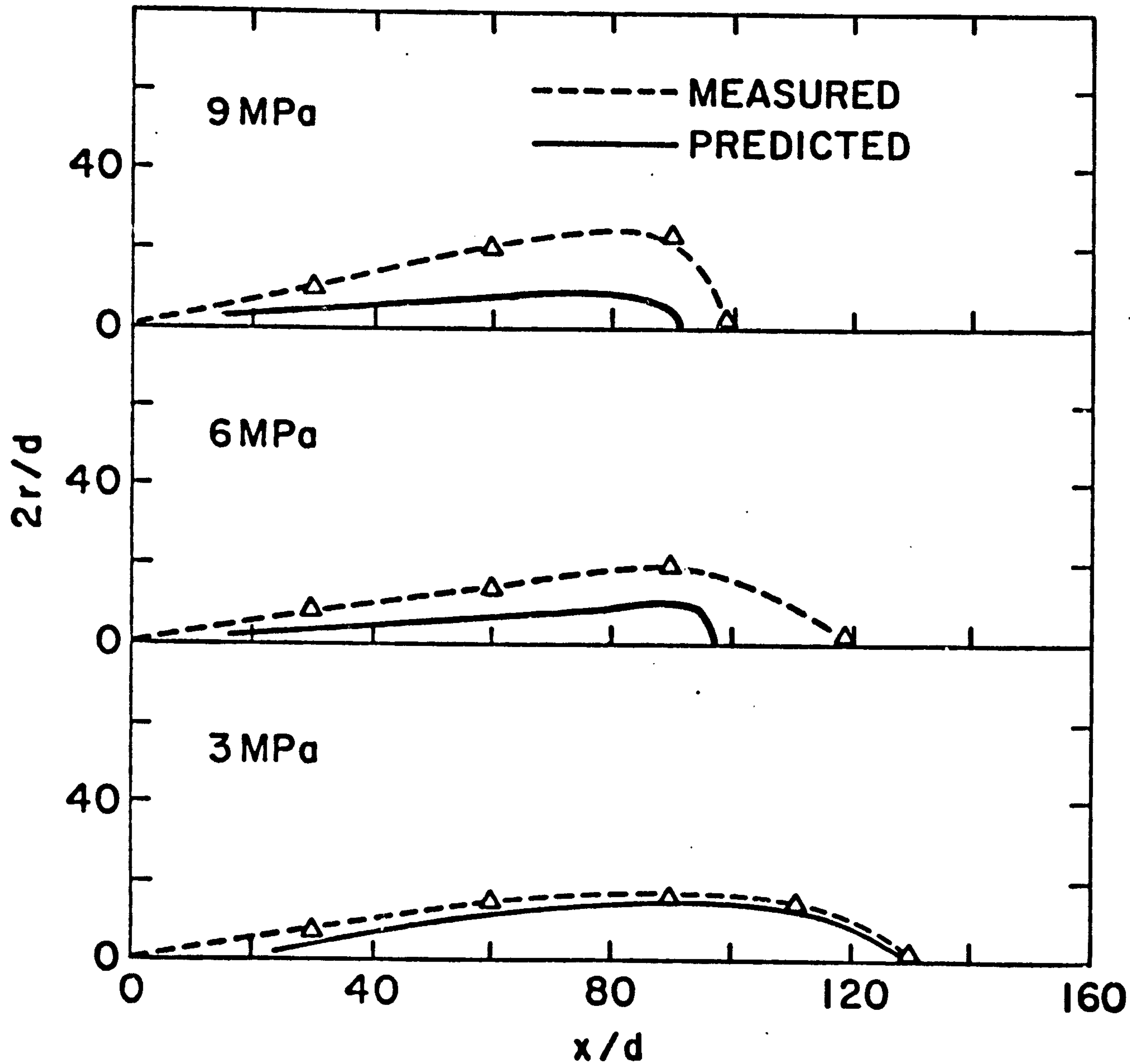
1. DROP/TURBULENCE INTERACTIONS, E.G., TURBULENT DISPERSION AND MODULATION.
2. INTERPHASE TRANSPORT PHENOMENA, E.G., TRANSIENT AND DEFORMATION EFFECTS, SLURRIES.
3. HIGH-PRESSURE SPRAYS, E.G., NEAR-CRITICAL-POINT PHENOMENA.



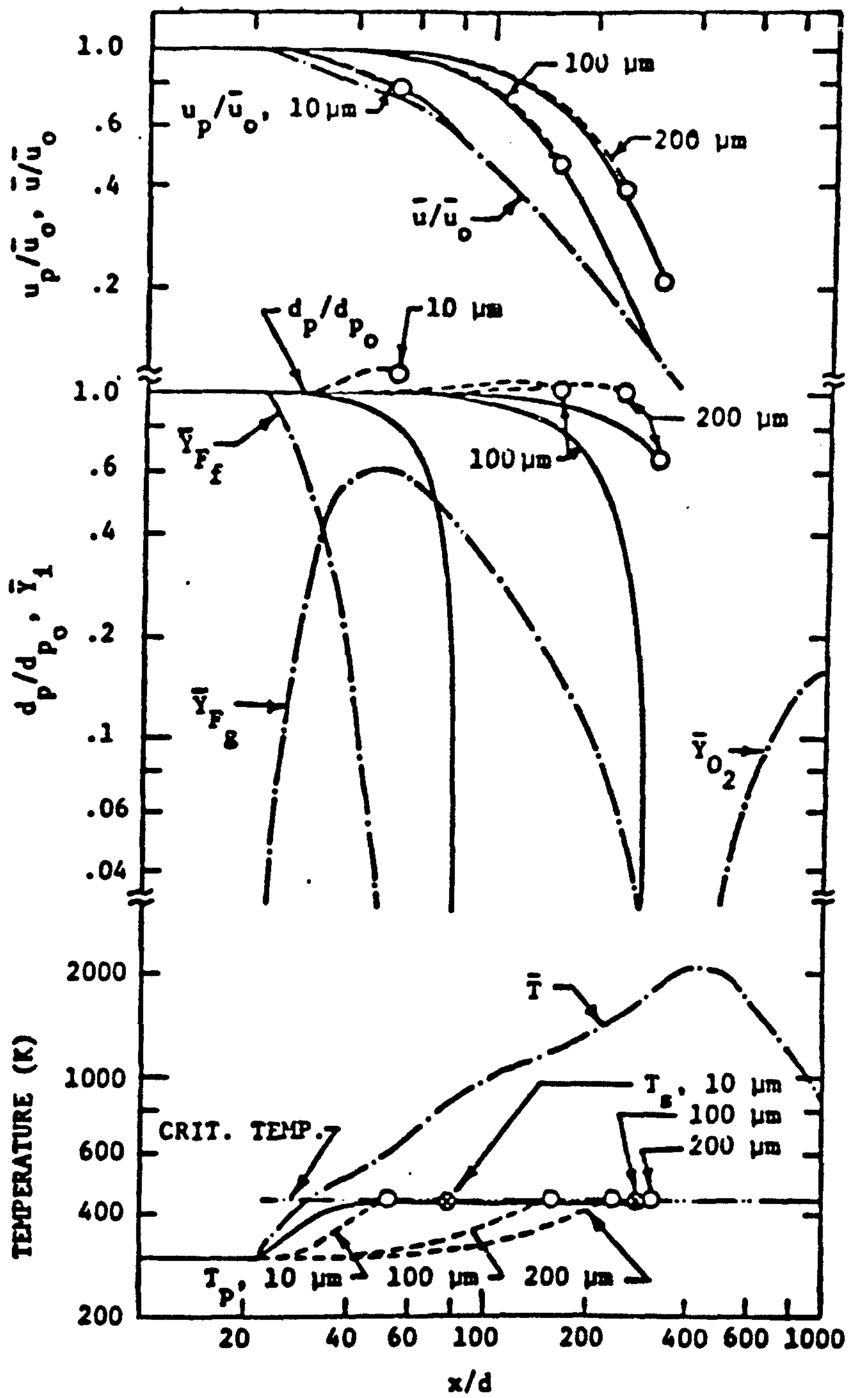
Equilibrium properties at the fuel surface for drops combusting in air at high pressures, form Canada and Faeth.



State relationships for an n-heptane spray burning in air at 3 MPa



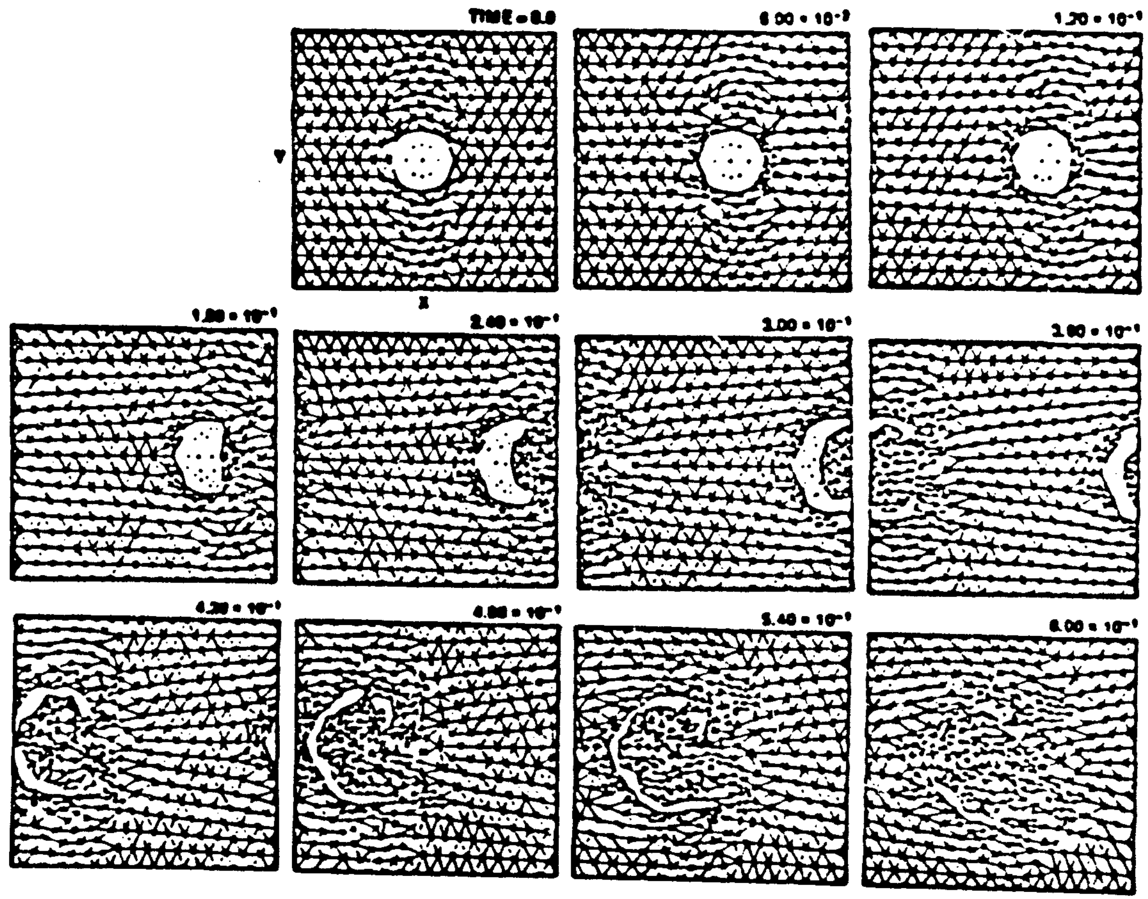
Predicted and measured spray boundaries for high pressure combustiag spays, from Mao et al.



Predictions of drop life histories for conditions where the thermodynamic critical point is exceeded, from Mao et al.

RESEARCH ISSUES FOR DILUTE SPRAYS

1. DROP/TURBULENCE INTERACTIONS, E.G., TURBULENT DISPERSION AND MODULATION.
2. INTERPHASE TRANSPORT PHENOMENA, E.G., TRANSIENT AND DEFORMATION EFFECTS, SLURRIES.
3. HIGH-PRESSURE SPRAYS, E.G., NEAR-CRITICAL-POINT PHENOMENA.
4. DROP SHATTERING.



Simulation of drop shattering, from Oran et al.

RESEARCH ISSUES FOR DILUTE SPRAYS

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2. INTERPHASE TRANSPORT PHENOMENA, E.G., TRANSIENT AND DEFORMATION EFFECTS, SLURRIES.
3. HIGH-PRESSURE SPRAYS, E.G., NEAR-CRITICAL-POINT PHENOMENA.
4. DROP SHATTERING.
5. DROP IGNITION AND EXTINCTION.

RESEARCH ISSUES FOR DILUTE SPRAYS

1. DROP/TURBULENCE INTERACTIONS, E.G., TURBULENT DISPERSION AND MODULATION.
2. INTERPHASE TRANSPORT PHENOMENA, E.G., TRANSIENT AND DEFORMATION EFFECTS, SLURRIES.
3. HIGH-PRESSURE SPRAYS, E.G., NEAR-CRITICAL-POINT PHENOMENA.
4. DROP SHATTERING.
5. DROP IGNITION AND EXTINCTION.

APPENDIX C

Non-Dilute Sprays

Figures by C. K. Law

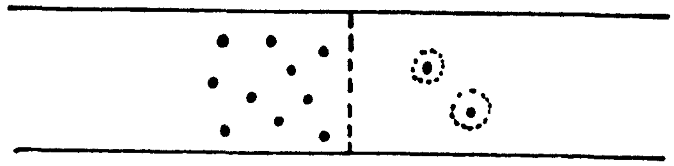
BEHAVIOR OF NON-DILUTE SPRAYS

C. K. LAW, U. C.-DAVIS

- RELEVANCE
- PROCESSES THAT ARE LIKELY TO BE
  - UNIMPORTANT
  - IMPORTANT
- RESEARCH NEEDS

- KEY PAPERS :
  - O'ROURKE AND BRACCO
  - FAETH

CLASSICAL 1-D PLANAR SPRAY MODELS



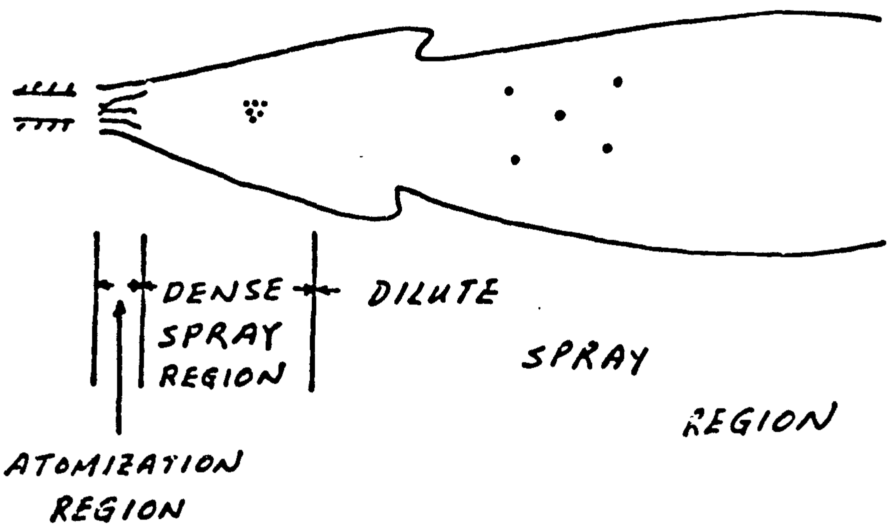
- PROXIMITY OF DROPLETS

  - $(F/A) = \dfrac{(1/6\,\pi\, d_s^3 \rho_l)}{(1/6\,\pi\, d_g^3 \rho_g)} = \left(\dfrac{d_s}{d_g}\right)^3 \left(\dfrac{\rho_l}{\rho_g}\right)$
  - $(F/A) = 0.05$
  - 1 ATM : $(d_g / d_s) \simeq \underline{25}$
  - COMPRESSION RATIO = 15 : $(d_g / d_s) \simeq \underline{15}$

- $(d_f / d_s) \sim \underline{O(10)}$

- THEREFORE INTERACTION CAN BE IMPORTANT

SPRAY JET CONFIGURATION



EXTENT OF DENSE SPRAY REGION
DEPENDING ON:

- RATE OF ENTRAINMENT
- RATE OF FUEL VAPOR GENERATION
- MODE OF ATOMIZATION
    - PRESSURE - ATOMIZED
    - AIR - ASSISTED

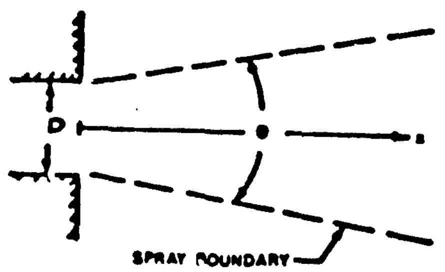
WHAT IS A DENSE SPRAY ?

- A SPRAY IS DENSE WHEN DROPLET INTERACTION EFFECTS ARE IMPORTANT, IN THAT INDIVIDUAL DROPLET PROCESSES CANNOT BE CONSIDERED TO TAKE PLACE IN AN INFINITE AMBIENCE.

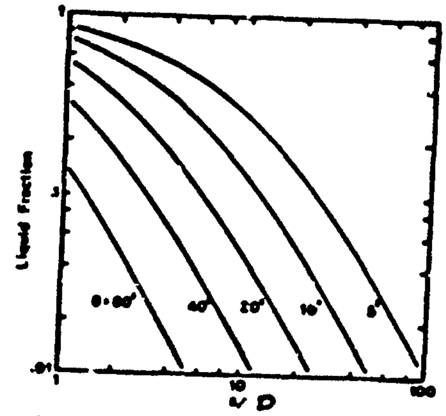
- LOOSELY SPEAKING, A DENSE SPRAY IS ONE WHOSE INTERIOR IS COLD AND FUEL RICH, THE DROPLETS ARE CLOSE TO EACH OTHER AND POSSIBLY ALSO MOVE WITH HIGH REYNOLDS NUMBERS.

- CHARACTERIZING PARAMETERS:
  - GEOMETRICAL : DROPLET SPACING, VOID FRACTION (ϕ), LIQUID FRACTION (α), DENSITY RATIO, ETC.
  - SCALAR PARAMETERS : OXYGEN CONCENTRATION, FUEL CONCENTRATION, TEMPERATURE.

EXTENT OF DENSE SPRAY REGION



Injector geometry for liquid fraction estimations.



Estimated liquid fraction variation in the axial direction for a solid cone spray.

$$\alpha = [1 + 2(x/D)\tan(\theta/2)]^{-2}$$

EARLIER WORKS SHOW SINGLE PARTICLES RESULTS APPLY QUITE WELL FOR PARTICLE SPACINGS EXCEEDING TWO DIAMETERS $\Rightarrow$ $\alpha = 0.08$.

THUS WITH $\theta = 12\text{-}25°$, $\alpha < 0.08$,

$x/D = 6\text{-}12$

PROCESSES LIKELY TO BE UNIMPORTANT

- STRICTLY SPEAKING, A DENSE SPRAY DESCRIPTION SHOULD ALSO BE APPLICABLE TO DILUTE SPRAYS. HOWEVER, BY TREATING THEM SEPARATELY, UNIMPORTANT PROCESSES CAN BE NEGLECTED IN EACH REGION, THEREBY SAVING COMPUTATIONAL EFFORT.

- NO CHEMICAL REACTIONS IN SPRAY INTERIOR ⇒ NO DROPLET OR GROUP BURNING ⇒ NO SUCH PHENOMENA AS EXTINCTION, NO_x AND SOOT FORMATION FROM DROPLET FLAMES.

- HOWEVER, SHOULD STILL ALLOW FOR (1) DIFFUSIONAL BURNING AT SPRAY EDGE FOR FLAME STABILIZATION, (2) DROPLET IGNITION FOR POSSIBLE TRANSITION TO DILUTE SPRAY REGION

PROCESSES LIKELY TO BE UNIMPORTANT

- LOW DROPLET TEMPERATURE ⇒ NO CRITICAL/SUPERCRITICAL PHENOMENA

- LOW DROPLET TEMPERATURE ⇒ NO DROPLET MICRO-EXPLOSION.

- DROPLET VAPORIZATION ?

PROCESSES/FACTORS LIKELY TO BE IMPORTANT

- DROPLET VAPORIZATION
- EXCHANGE PROCESSES IN TWO-PHASE MEDIA
- DROPLET COLLISION
- MODIFICATION OF TURBULENCE PROPERTIES

PREVIOUS WORK ON DROPLET VAPORIZATION

- EARLIER EXPERIMENTAL WORK OF CHIGIER AND OF ONUMA ET AL. SUGGEST ABSENCE OF DROPLET BURNING IN SPRAY INTERIOR.

- ANALYSES DEMONSTRATE THE POSSIBILITY OF SATURATION:

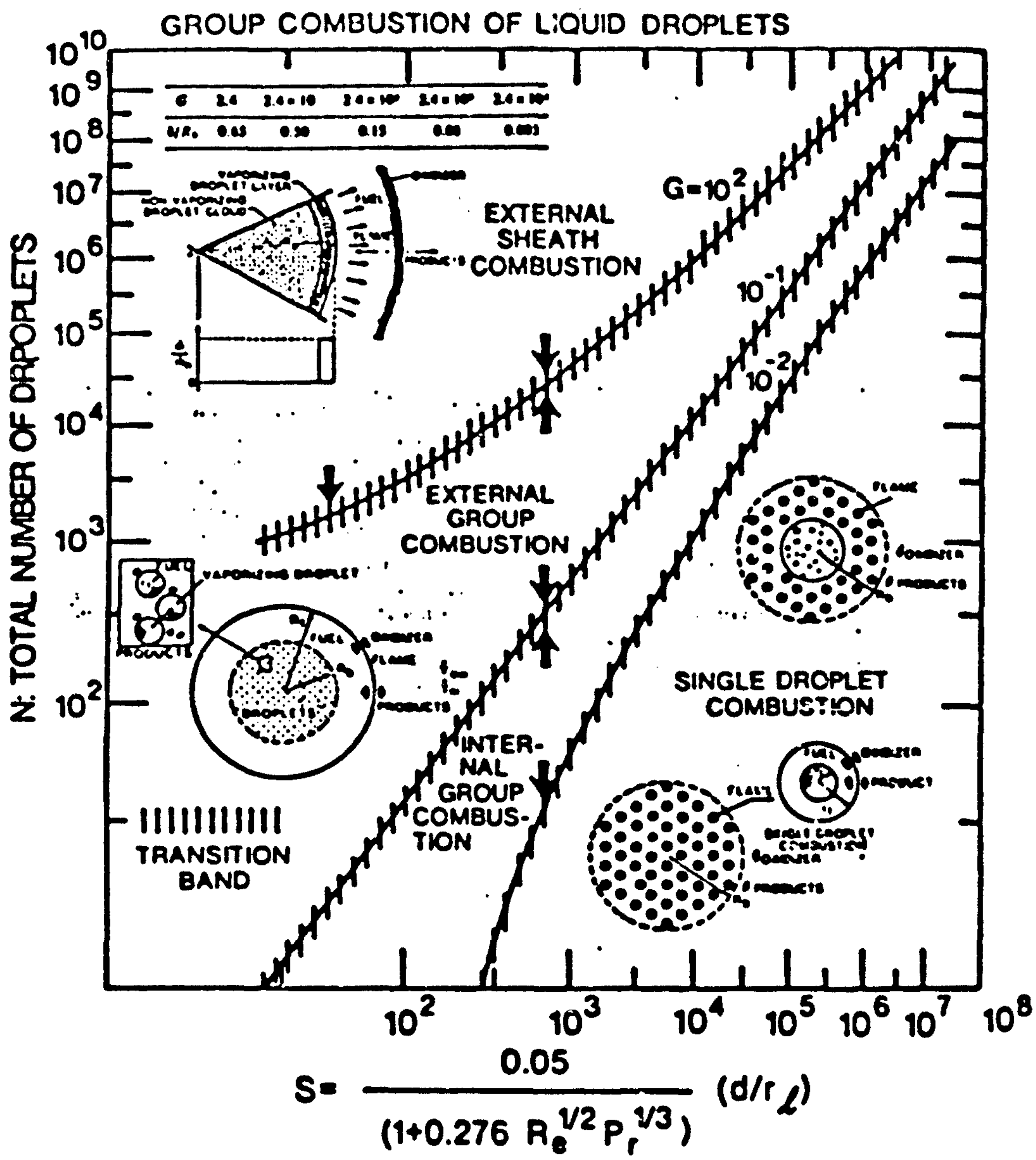
  1-D SPRAY VAPORIZATION (LAW)

  DROPLET-IN-BUBBLE MODEL (TISHKOFF)

- ANALYSES OF DROPLET ARRAYS DEMONSTRATE REDUCTION IN BURNING RATE DUE TO INTERACTION (BRZUSTOWSKI, ROSNER, LABOWSKY, DEUTCH, UMEMURA)

- GROUP COMBUSTION MODELS (CHIU, ROSNER) IDENTIFY VARIOUS MODES OF SPRAY BURNING

- EXPERIMENTAL WORK (BOWMAN, BRZUSTOWSKI, LAW, SANGIOVANNI) DEMONSTRATE REDUCTION IN BURNING RATE DUE TO INTERACTION.



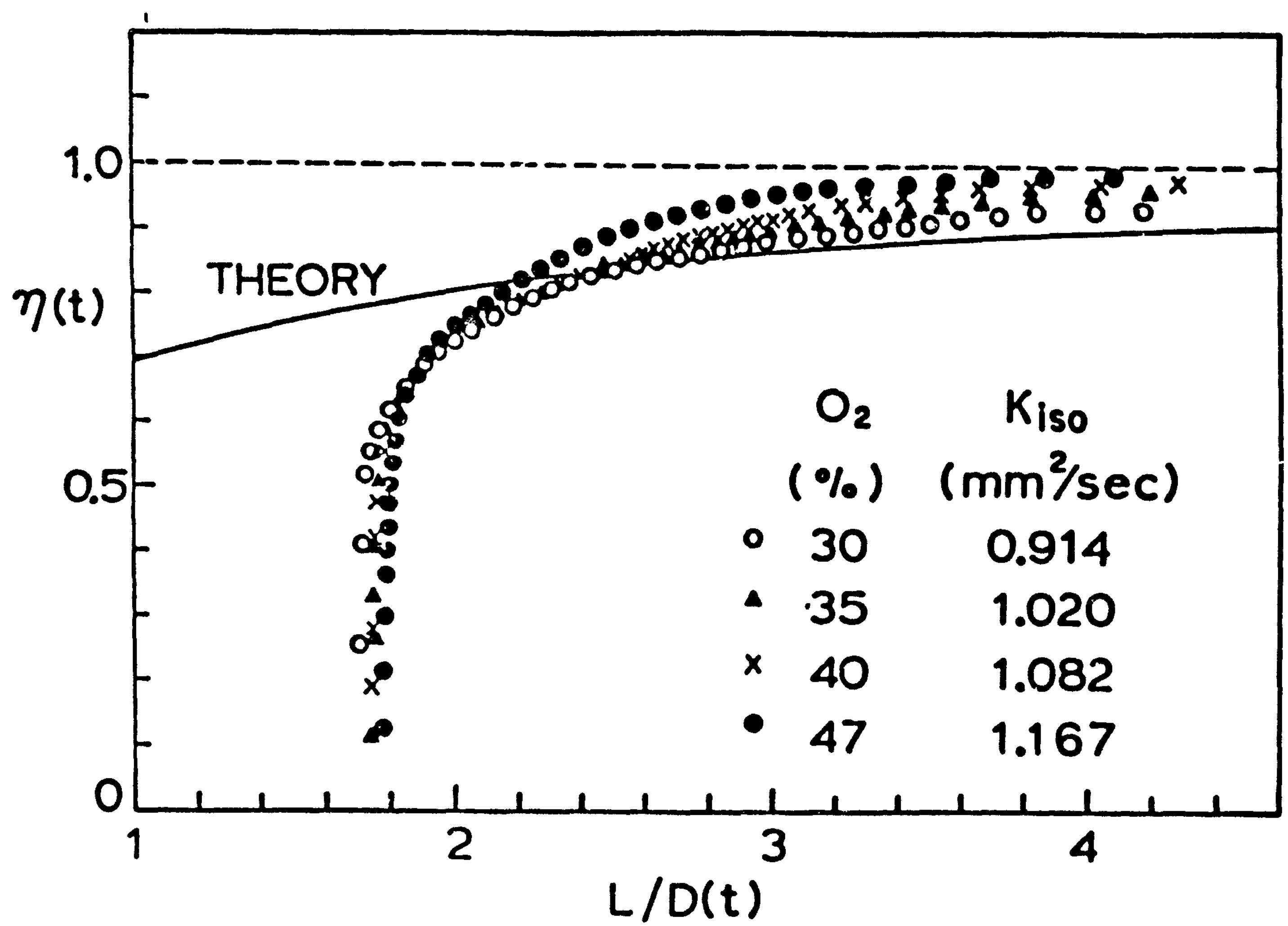
Four group combustion modes of a droplet cloud.

PREVIOUS WORK ON DROPLET VAPORIZATION

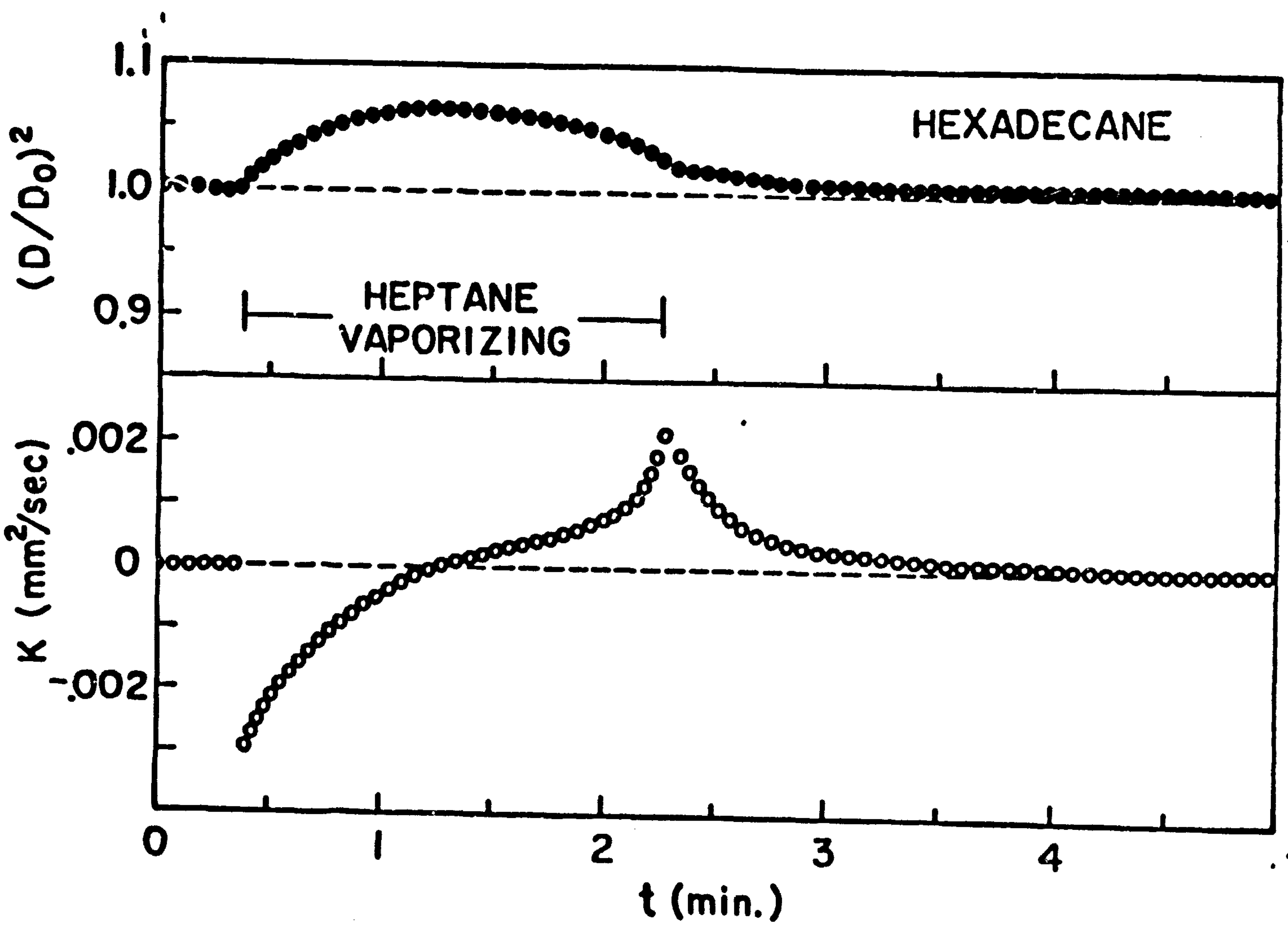
- EXPERIMENTAL WORK (LAW) FURTHER DEMONSTRATES:
  (1) SHORT-RANGE EFFECT OF DROPLET INTERACTION ON GASIFICATION RATE
  (2) POSSIBILITY OF CONDENSATION OF VAPOR A ON DROPLET B.

- CONVECTIVE SOLUTIONS OF PERIODIC ARRAYS (SIRIGNANO)

- MODELS THAT HAVE POTENTIAL FOR INCORPORATION IN SPRAY MODELING:
  (1) DROPLET-IN-BUBBLE
  (2) MULTI-DROPLET SOLUTION WITH SCREENING DISTANCE
  (3) PERIODIC DROPLET GROUPS



1.0
0.5
0
$\eta(t)$
THEORY
1
2
3
4
L/D(t)
O_2
(%)
30
35
40
47
K_{iso}
(mm^2/sec)
0.914
1.020
1.082
1.167



HEXADECANE
HEPTANE VAPORIZING
$(D/D_o)^2$
1.1
1.0
0.9
K (mm²/sec)
.002
0
-.002
0
1
2
3
4
t (min.)

DROPLET VAPORIZATION IN DENSE SPRAY

- $\dot{m} \sim \ln(1+B)$; $B = c_p(T_g - T_s)/L$
  - ACCURATE DETERMINATION OF T_g, T_s NEEDED
  - ACCURATE TREATMENT OF PHASE EQUILIBRIUM NEEDED, ALLOWING FOR SATURATION AND CONDENSATION

- $\dot{m} \sim B \Rightarrow$ SIMPLIFICATION IN ANALYTICAL WORK.

- SLOW RATE OF VAPORIZATION COULD CAUSE PERPETUAL UNIFORMIZATION OF DROPLET INTERIOR, IMPLYING:

  (1) SPATIALLY-UNIFORM, TEMPORALLY-VARYING DROPLET TEMP. AND COMPOSITION

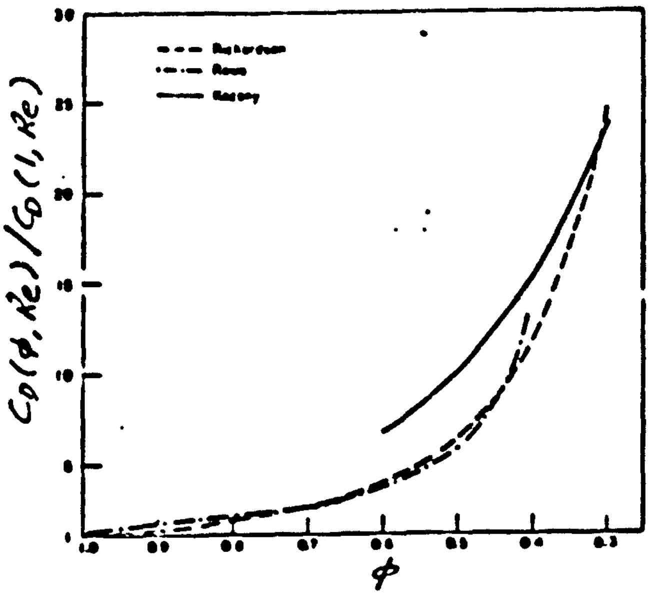
  (2) VOLATILE COMPONENT PREFERENTIALLY GASFIED

  (3) SIGNIFICANT SIMPLIFICATION IN COMPUTATION

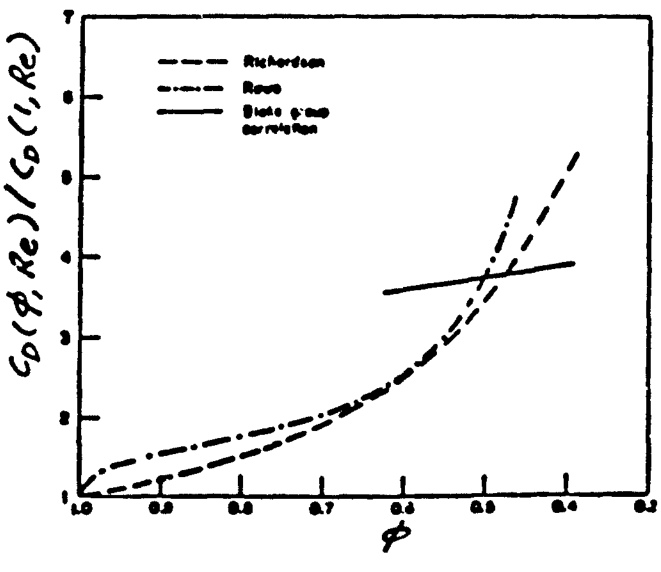
DROPLET VAPORIZATION IN DENSE SPRAYS

- IF INTERIOR IS PERPETUALLY SATURATED, RATE OF GASIFICATION $\propto$ RATE OF ENTRAINMENT OF HOT GAS.

EXCHANGE COEFFICIENTS



Experimental correlations for the ratio $C_D(\ ,Re)/C_D(1,Re)$ for low Re



Experimental correlations for the ratio $C_D(\ ,Re)/C_D(1,Re)$ for $Re = 500$

O'ROURKE AND BRACCO USED:

$$C_D(\phi, Re) = \frac{24}{Re}\left[\phi^{-2.65} + \frac{Re^{2/3}}{6}\phi^{-1.78}\right]$$

$$Nu(\phi, Re) = 2\left[\phi^{-1.75} + 0.3\left(\frac{Re}{\phi}\right)^{1/2} Pr^{1/3}\right]$$

DROPLET COALESCENCE

- EXPERIMENTAL WORK OF REITZ AND BRACCO SHOWS ATOMIZATION PRODUCES VERY SMALL DROPLETS (~ FEW μm)

- EXPERIMENTAL WORK OF KADOTA AND HIROYASU SHOWS MUCH BIGGER DROPLETS (~ TENS OF μm) FURTHER DOWNSTREAM OF NOZZLE

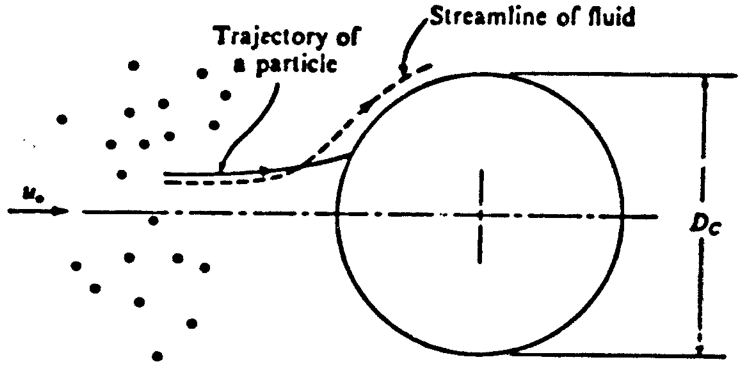
- NUMERICAL SOLUTION OF O'ROURKE AND BRACCO SHOWS THE DIFFERENCE IS CAUSED BY DROPLET COALESCENCE

IF THIS IS TRUE, THEN DROPLET COALESCENCE COULD HAVE MUCH STRONGER EFFECT THAN DROPLET VAPORIZATION IN DETERMINING THE DROPLET SIZE

PHENOMENOLOGY OF DROPLET COLLISION

- VERY DIFFERENT DROPLET SIZES :

  ABSOPTION OR DEFLECTION



Impaction of particles with a body.

- SIMILAR DROPLET SIZES :

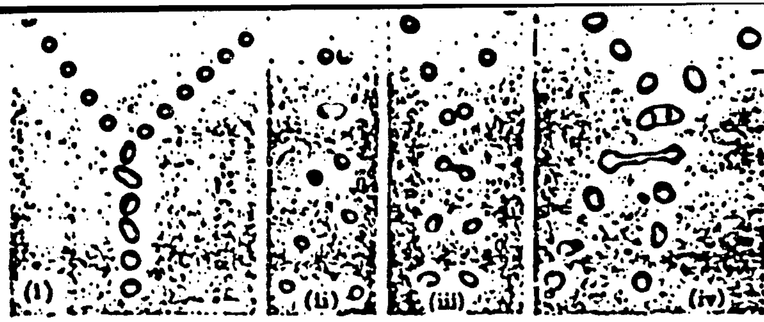
  (1) REBOUND, CANNOT OVERCOME AIR FILM

  (2) PERMANENT COALESCENCE

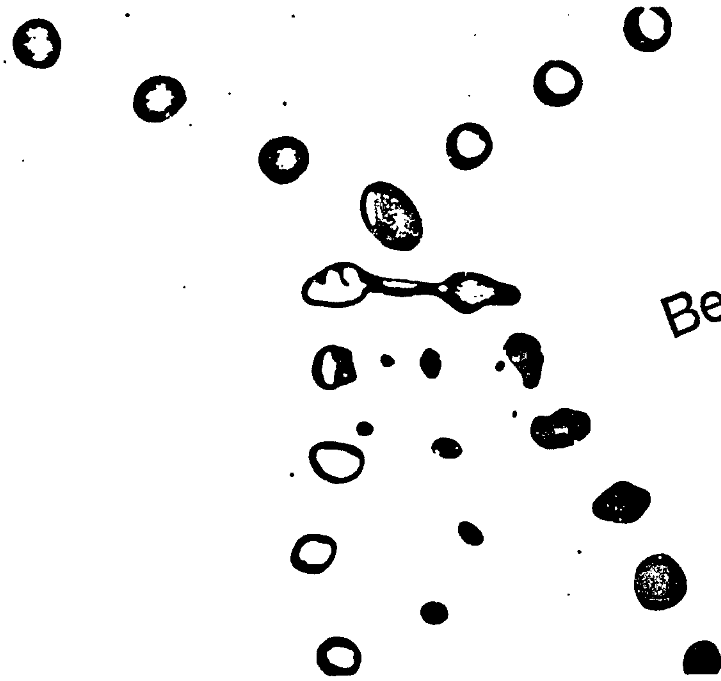
  (3) SEPARATION WITHOUT CHANGE

  (4) SEPARATION WITH SATELLITES

  (5) SPATTERING



Drop collision categories: (i) permanent coalescence; (ii) bouncing; (iii) separation without satellites; (iv) separation with satellites.



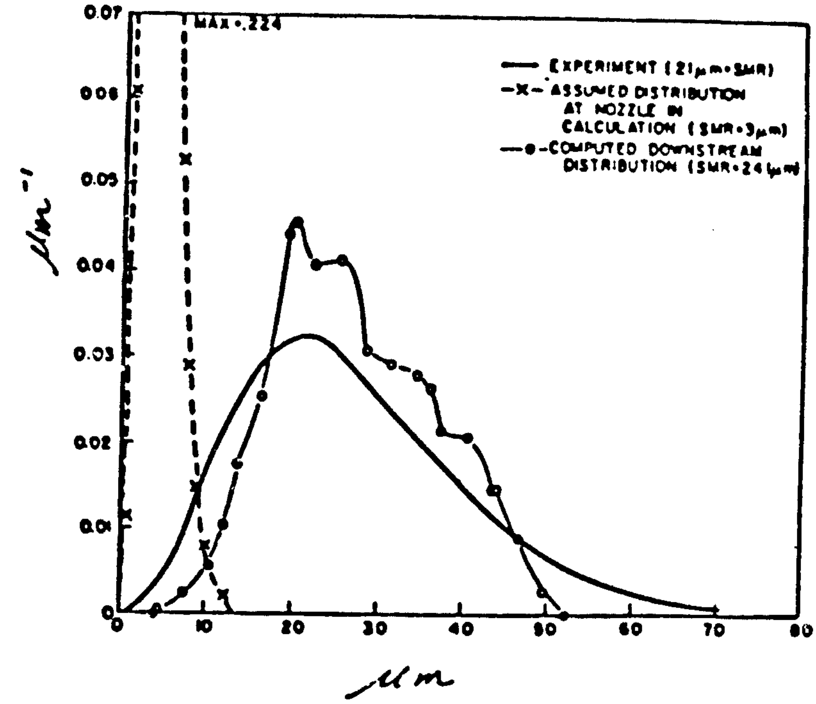
The coalescence and separation of equally sized water drops. $R = r = 650\ \mu m$. $U = 2.0\ m\,s^{-1}$.

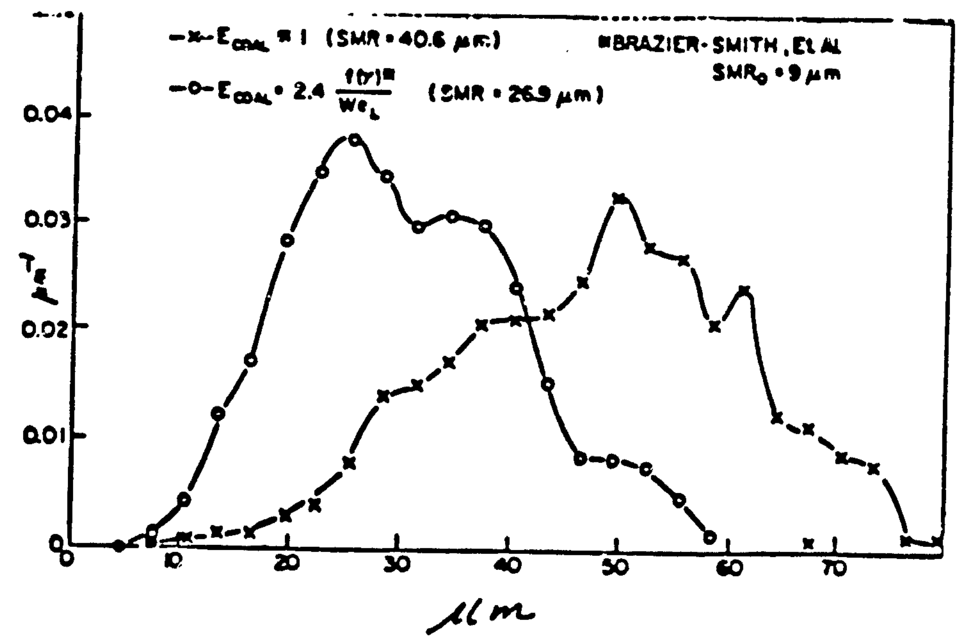
CRITERION FOR COALESCENCE:

COALESCED DROPLET WILL SEPARATE IF ITS ROTATIONAL ENERGY EXCEEDS THE INCREASE IN SURFACE ENERGY NEEDED TO CREATE THE TWO DROPLETS

DROP VOLUME DISTRIBUTION,

$$\frac{1}{V_r}\frac{dV(r)}{dr}$$





Effect of altering the coalescence efficiency on computed drop volume distributions when SMR_0 = 9 μm

EFFECTS OF DROPLETS ON TURBULENCE

- TURBULENT ENERGY IS DISSIPATED IN ACCELERATING THE DROPLETS
- EDDY VISCOSITY IS DECREASED BY THE RATIO

$$(1 + \sigma_p / \rho)^{-1/2}$$

WHERE σ_p = MASS CONCENTRATION OF DROPLETS

ρ = GAS DENSITY

RESEARCH NEEDS

- EXCHANGE PROCESSES (INCLUDING DROPLET VAPORIZATION) IN TWO-PHASE MEDIA:

  THEORY: LOW AND MEDIUM Re FLOW

  LOW AND HIGH VOID FRACTION

  EXPT. : DENSE PARTICULATE FLOWS

  DENSE DROPLET FLOWS

- DROPLET COLLISION/COALESCENCE EXPT.:
  - SMALL DROPLETS
  - USE FUEL INSTEAD OF WATER
  - COLLISION OF DROPLETS IN TANDEM

- TURBULENCE MODELING OF DENSE TWO-PHASE FLOWS

- EFFECTS OF AIR-ASSISTED ATOMIZATION

- OPTICAL PROBING OF DENSE SPRAYS

APPENDIX D

Atomization

Figures by R. D. Reitz

REVIEW OF LIQUID JET ATOMIZATION

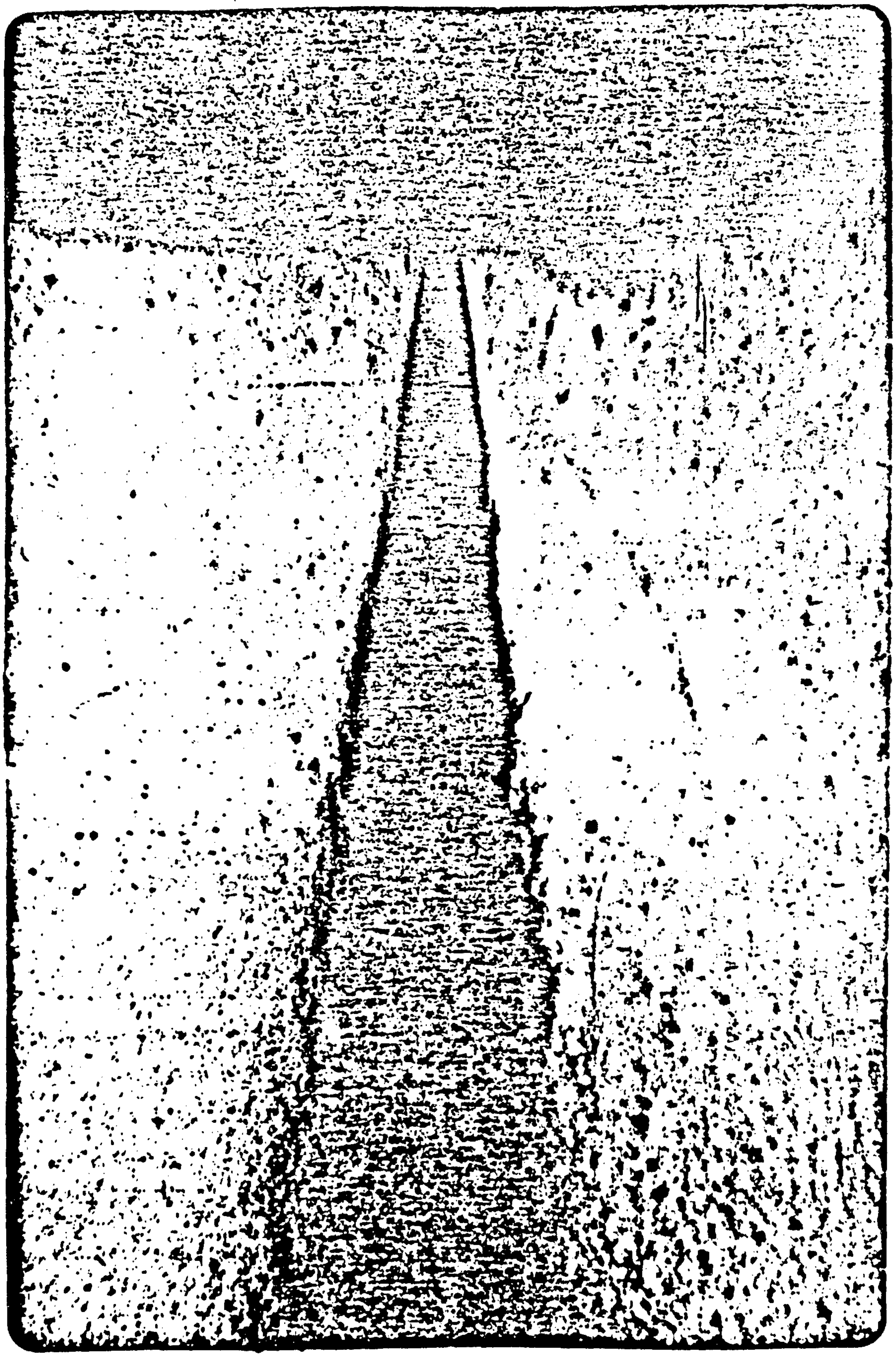
Rolf D. Reitz
Fluid Mechanics Department
General Motors Research Laboratories

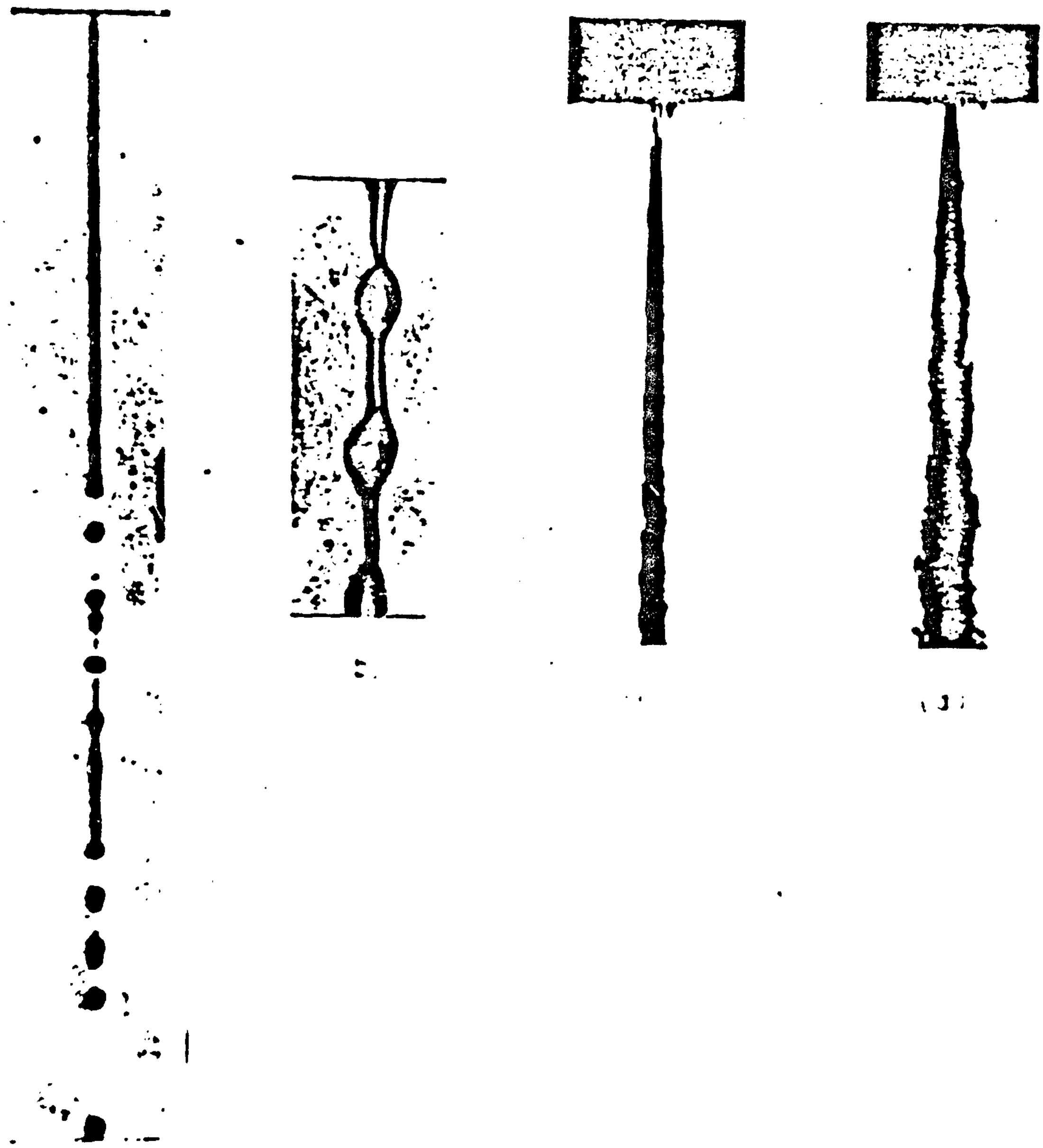
for presentation at

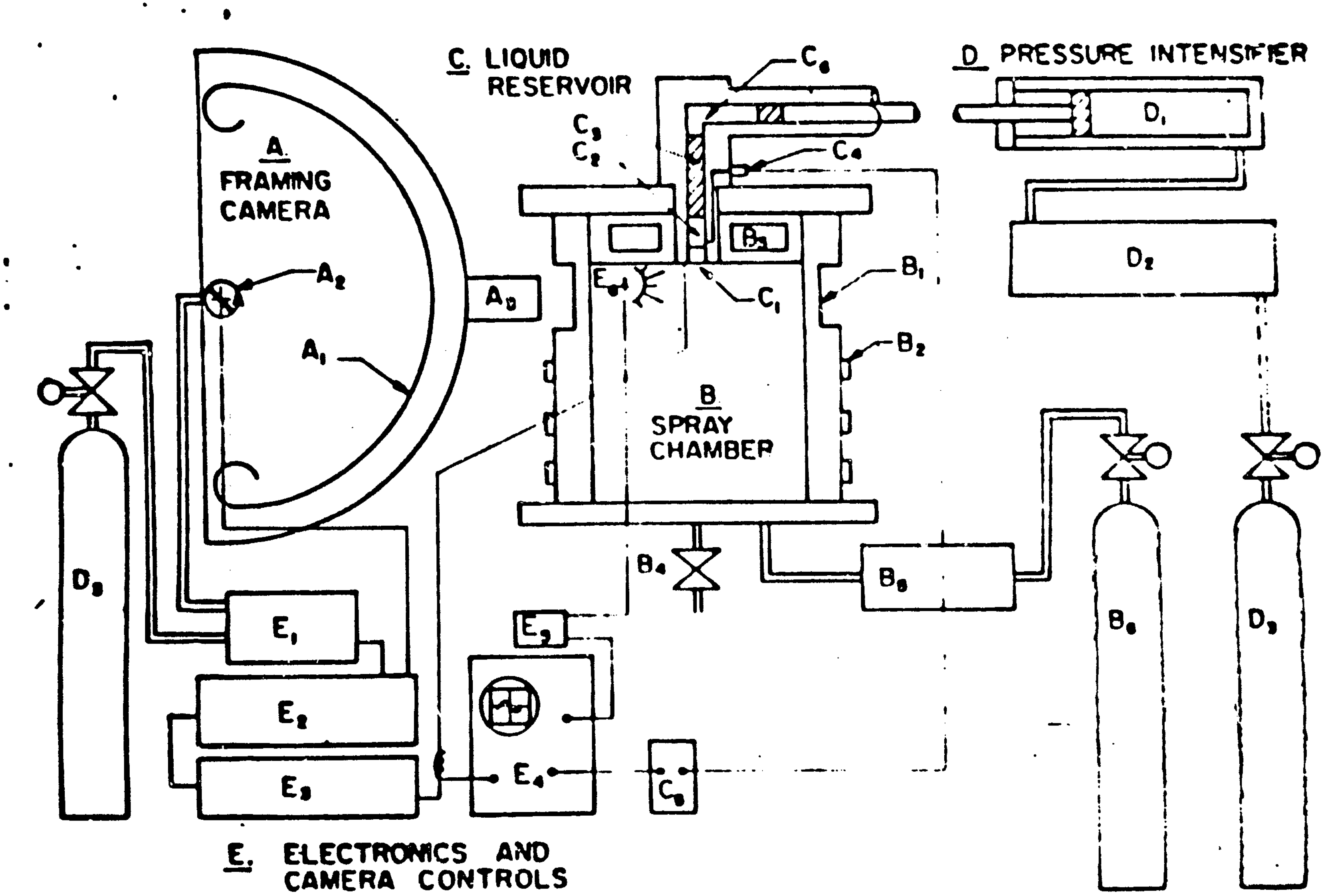
Specialists Meeting on Atomization and Nondilute Sprays
Sandia National Laboratories,
Livermore, CA.
March 20-21, 1985.

ABSTRACT

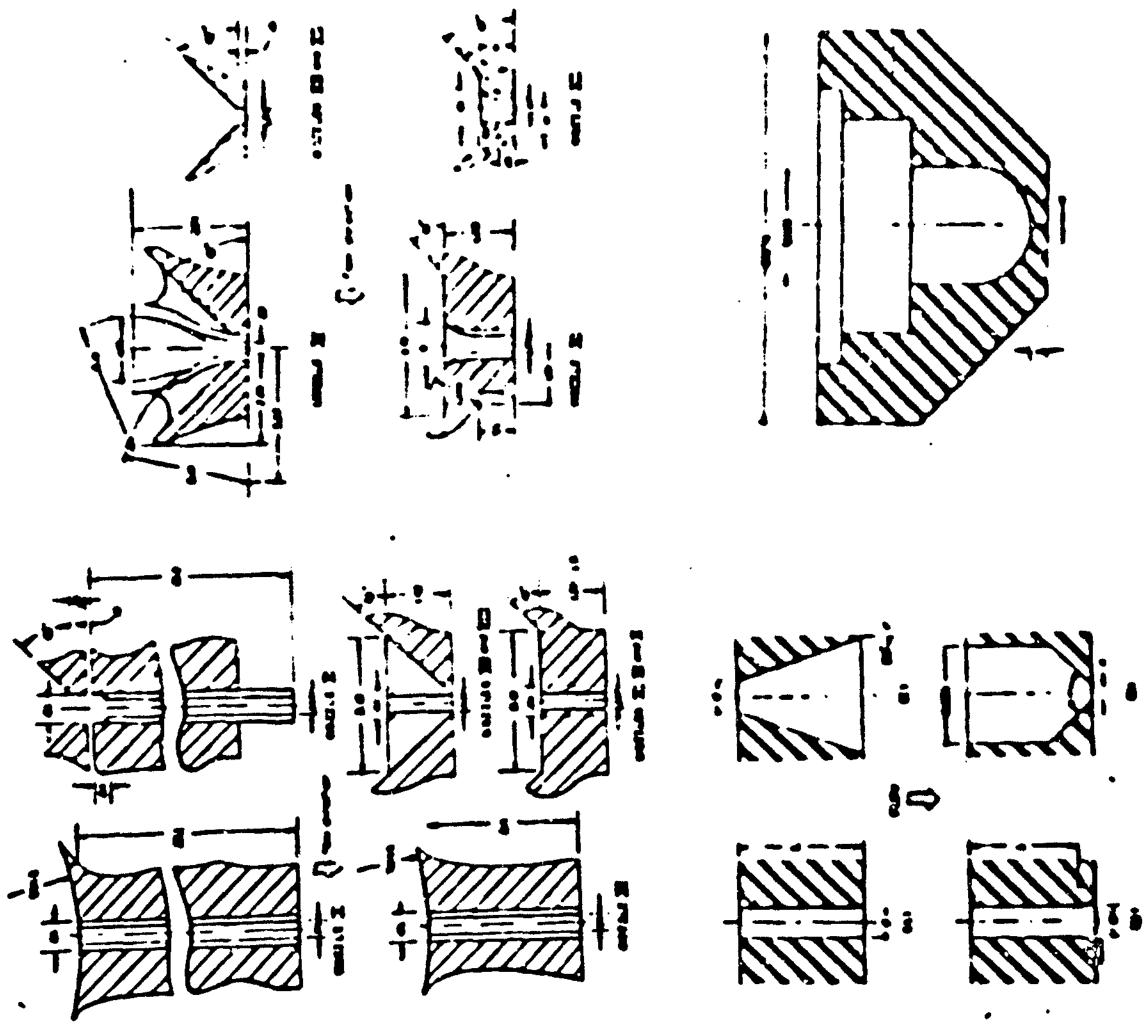
In the atomization regime of a round liquid jet, a diverging spray is observed immediately at the nozzle exit. The mechanism that controls atomization has not yet been determined even although several have been proposed. An evaluation of existing theories shows that aerodynamic effects, liquid turbulence, jet velocity profile rearrangement effects, and liquid supply pressure oscillations each cannot alone explain available experimental data. However, a mechanism that combines liquid-gas aerodynamic interaction with nozzle geometry effects is consistent with the data. But the specific process by which the nozzle geometry influences atomization still remains to be identified.

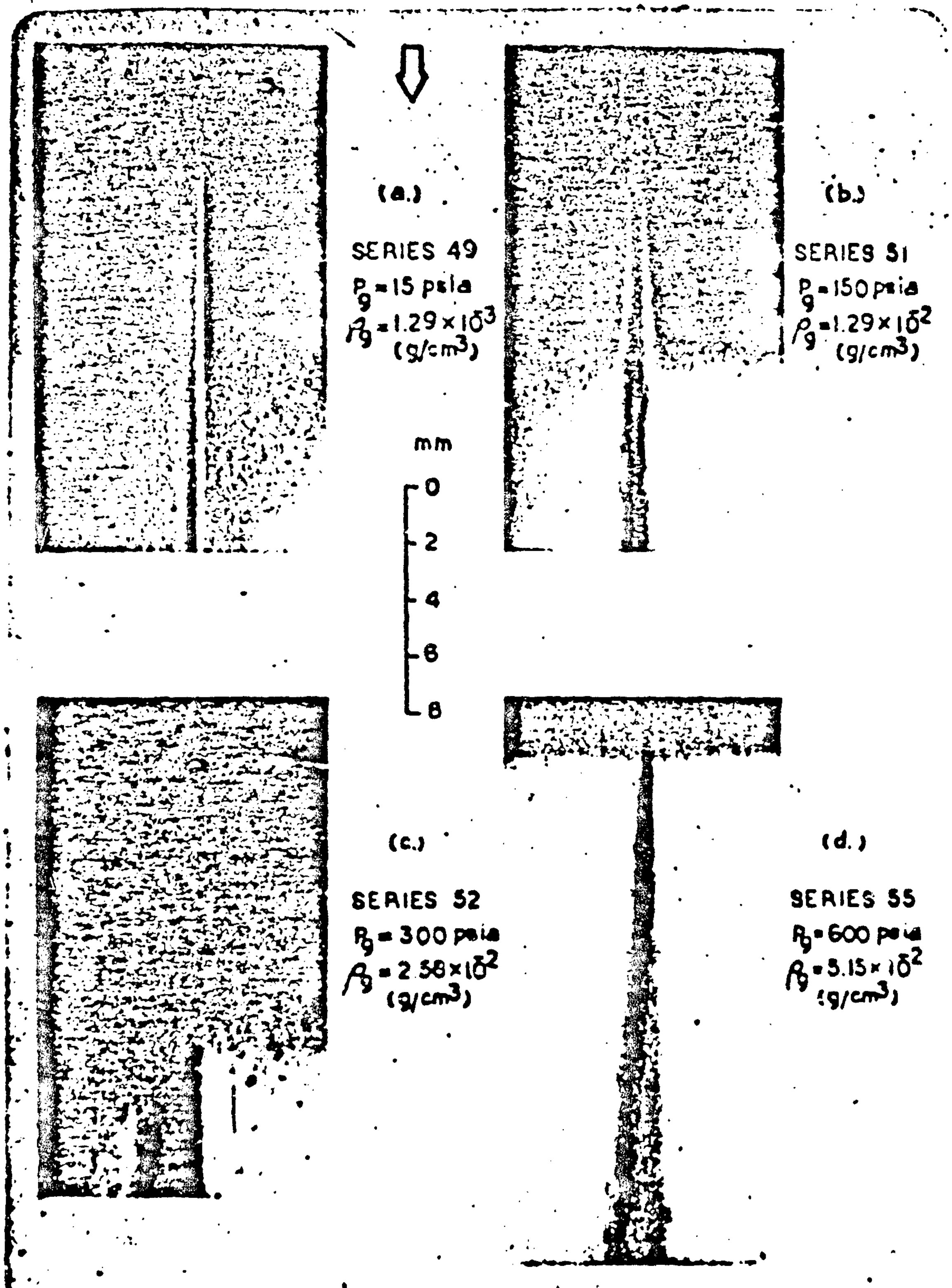




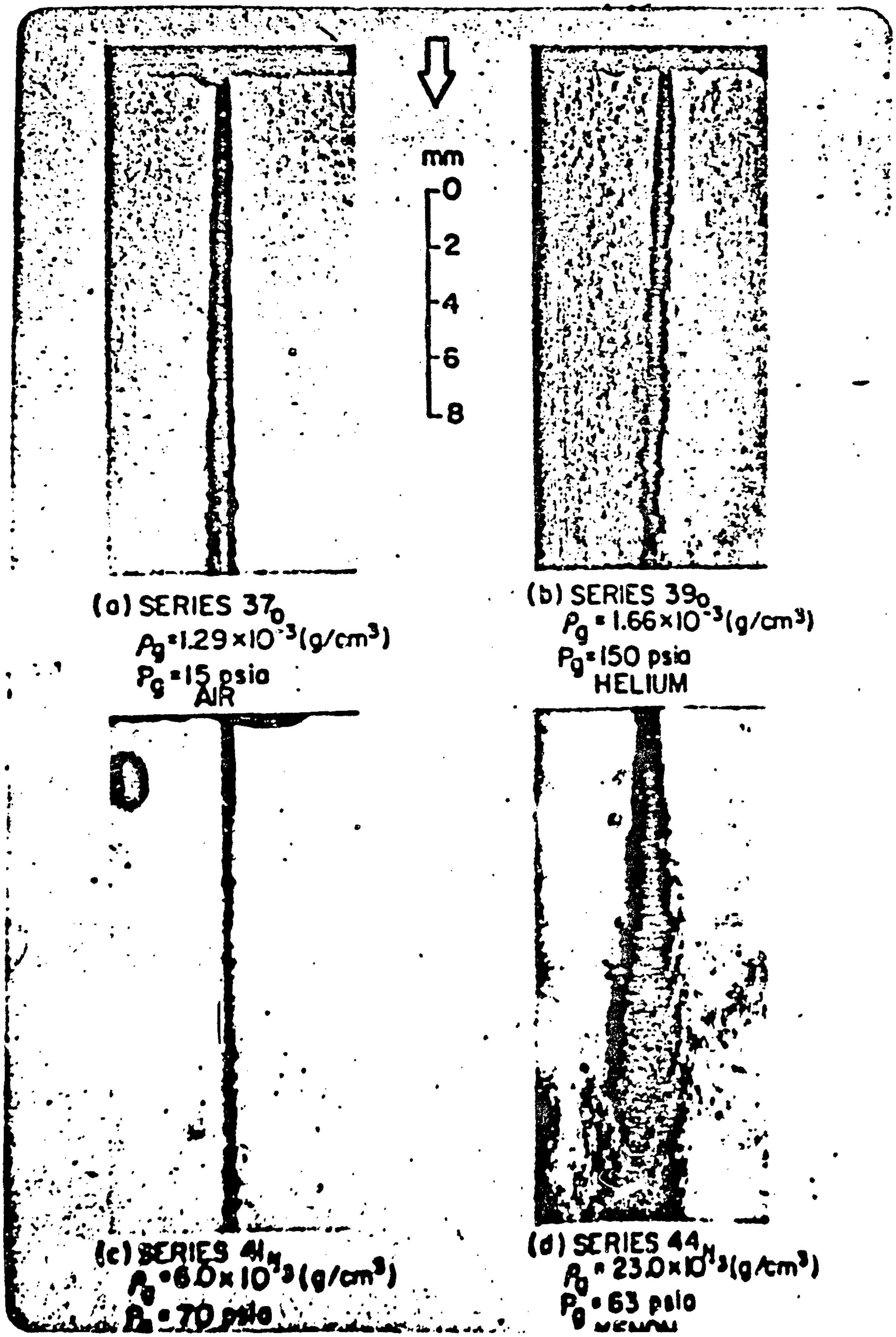

A. FRAMING CAMERA
A_1
A_2
A_3
B. SPRAY CHAMBER
B_1
B_2
B_3
B_4
B_5
B_6
C. LIQUID RESERVOIR
C_1
C_2
C_3
C_4
C_5
C_6
D. PRESSURE INTENSIFIER
D_1
D_2
D_3
D_3
E. ELECTRONICS AND CAMERA CONTROLS
E_1
E_2
E_3
E_4
E_5
E_6

	Reitz (Refs. 2,3,4)	Su and Wu (Refs. 5,6)
Test Liquid	Water, Glycerol, and Their Mixtures	Water, n-Hexane, and n-Tetradecane
ρ_ℓ	0.998 - 1.261	0.763 - 0.998
P_ℓ	3.9 - 18.0	11.1 - 107.6
μ_ℓ	0.010 - 17.596	0.0032 - 0.0218
σ_ℓ	63.0 - 72.8	18.4 - 72.8
T_ℓ	room temp.	room temp.
Ambient Gas	N_2, He, and Xe	N_2
$\rho_g \times 10^3$	1.1 - 51.5	1.2 - 48.7
P_g	0.1 - 4.2	0.1 - 4.2
$\mu_g \times 10^4$	1.70 - 2.26	1.70
T_g	room temp.	room temp.
Nozzle Geometries	9	7
d	343	254, 343, and 660
L/d	0.5 - 85	≈0 and 4.0
Argument of f	1.3×10^{-4} - 1.6×10^{3}	0.4 - 420
$\rho_g/\rho_\ell \times 10^3$	1.1 - 15.6	1.8 - 73.2





PHOTOGRAPHS SHOWING EFFECT OF CHAMBER GAS COMPRESSION ON STEADY STATE JET BREAKUP — GAS N_2, ΔP = 1600 psia WATER, NOZZLE XII

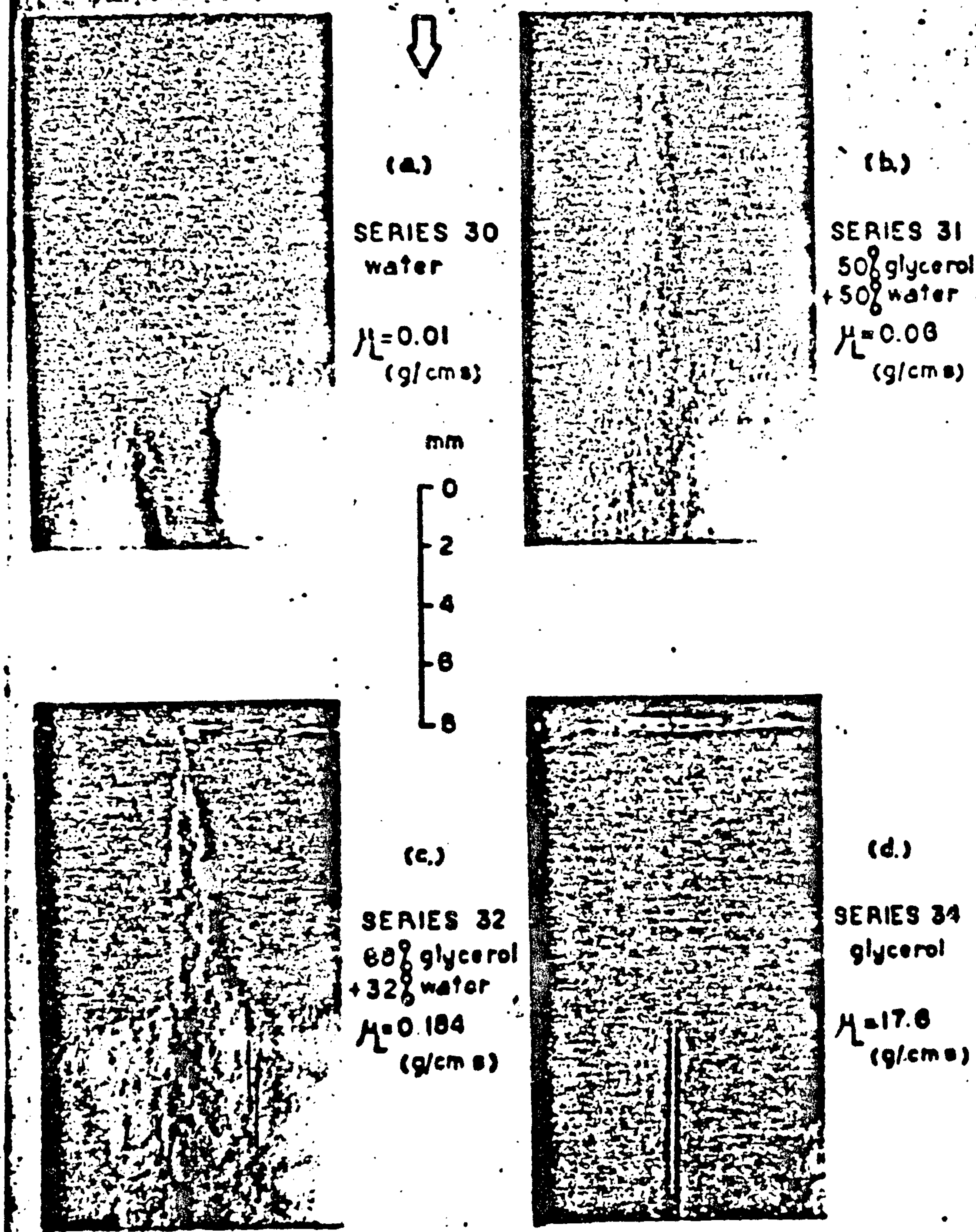


(a) SERIES 37_O
$\rho_g = 1.29 \times 10^{-3}$ (g/cm³)
$P_g = 15$ psia
AIR

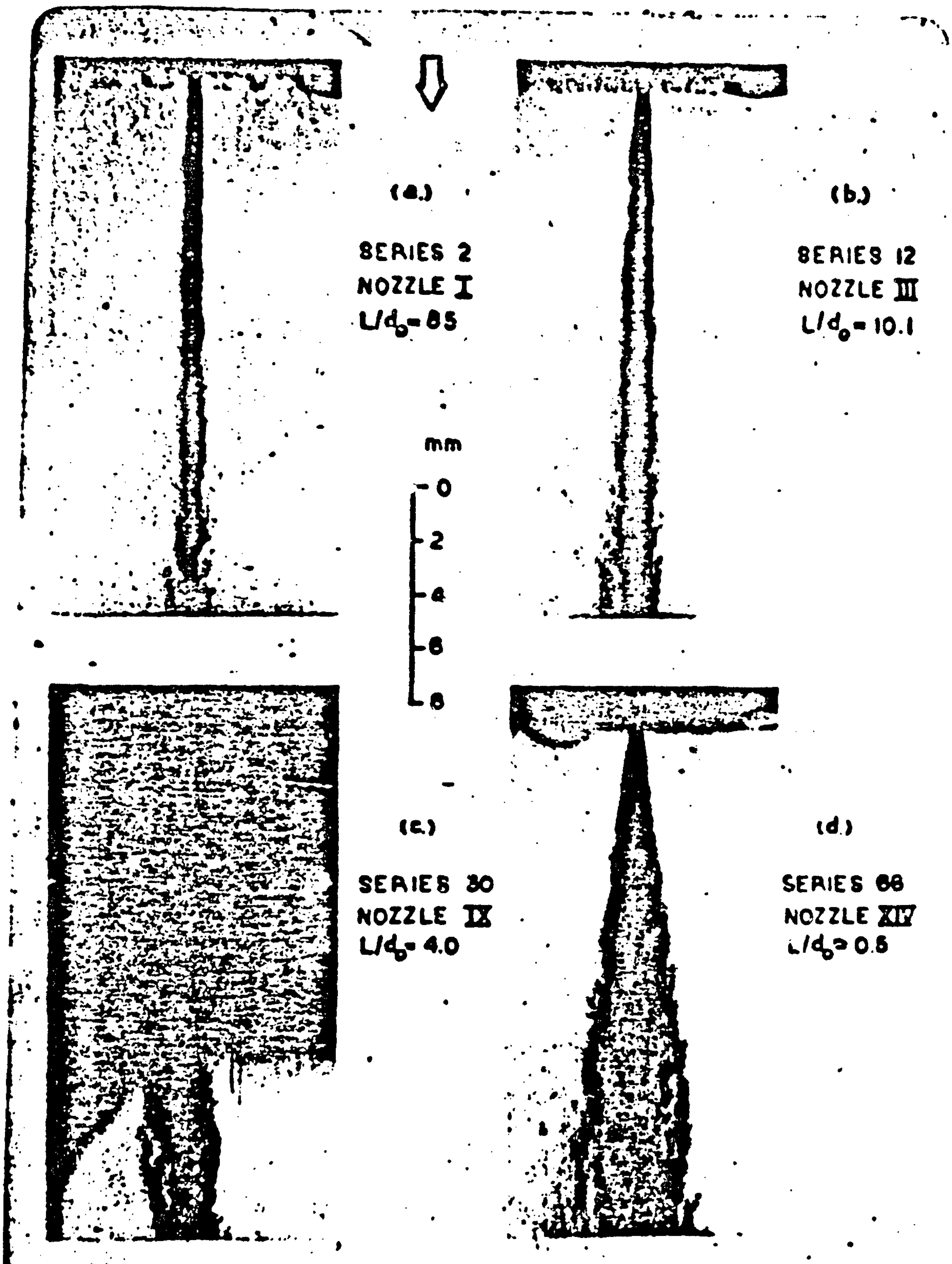
(b) SERIES 39_O
$\rho_g = 1.66 \times 10^{-3}$ (g/cm³)
$P_g = 150$ psia
HELIUM

(c) SERIES 41_H
$\rho_g = 6.0 \times 10^{-3}$ (g/cm³)
$P_g = 70$ psia

(d) SERIES 44_H
$\rho_g = 23.0 \times 10^{-3}$ (g/cm³)
$P_g = 63$ psia



PHOTOGRAPHS SHOWING EFFECT OF TEST LIQUID ON STEADY STATE JET BREAKUP – CHAMBER GAS N_2, 300 psia, ΔP = 1700 psia, NOZZLE IX



PHOTOGRAPHS SHOWING EFFECT OF NOZZLE PASSAGE LENGTH ON STEADY STATE JET BREAKUP—CHAMBER GAS N_2 300 psia, ΔP=1800 psia WATER INJECTIONS

EVALUATION OF PROPOSED ATOMIZATION MECHANISMS

1. Aerodynamic interaction – dependence on nozzle geometry
2. Pipe turbulence – stable jets from nozzles with large L/d:
3. Wall boundary layer profile rearrangement – dependence on ρ_g
4. Cross section velocity profile rearrangement – stability of Poiseuille flows (high liquid viscosity)
5. Supply pressure oscillations – atomization with constant pressure
6. Cavitation – atomization with cavitation-free nozzles

CAN EXPLAIN EXPERIMENTAL TRENDS

Supplemented Aerodynamic interaction theory

Mechanism of atomization of a liquid jet

Phys. Fluids vol. 25 No. 10, October 1982

R. D. Reitz and F. V. Bracco
Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, New Jersey 08544

$$\frac{\partial u_1}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}(r v_1) = 0,$$

$$\frac{\partial u_1}{\partial t} + U_1(r)\frac{\partial u_1}{\partial z} + v_1\frac{dU_1}{dr}$$

$$= -\frac{1}{\rho_1}\frac{\partial p_1}{\partial z} + \nu_1\left[\frac{\partial^2 u_1}{\partial z^2} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_1}{\partial r}\right)\right],$$

$$\frac{\partial v_1}{\partial t} + U_1(r)\frac{\partial v_1}{\partial z}$$

$$= -\frac{1}{\rho_1}\frac{\partial p_1}{\partial r} + \nu_1\left[\frac{\partial^2 v_1}{\partial z^2} + \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}rv_1\right)\right]. \quad (1)$$

$$\phi_1 = \Phi_1(r)e^{ikz+\omega t}, \quad \psi_1 = \Psi_1(r)e^{ikz+\omega t},$$

$$v_1 = \frac{\partial\eta}{\partial t} + U\frac{\partial\eta}{\partial z}, \quad (2a)$$

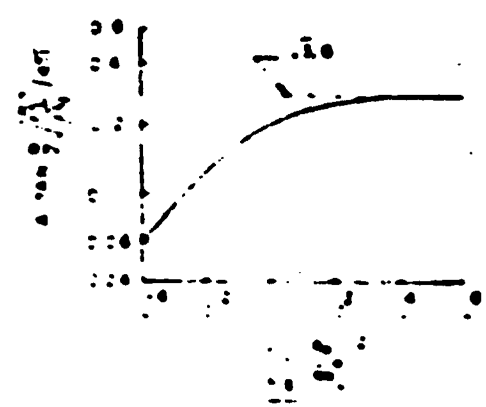
$$\frac{\partial u_1}{\partial r} = -\frac{\partial v_1}{\partial z}, \quad (2b)$$

$$-p_1 + 2\mu_1\frac{\partial v_1}{\partial r} - \frac{\sigma}{a^2}\left(\eta + a^2\frac{\partial^2\eta}{\partial z^2}\right) + p_2 = 0 \quad (2c)$$

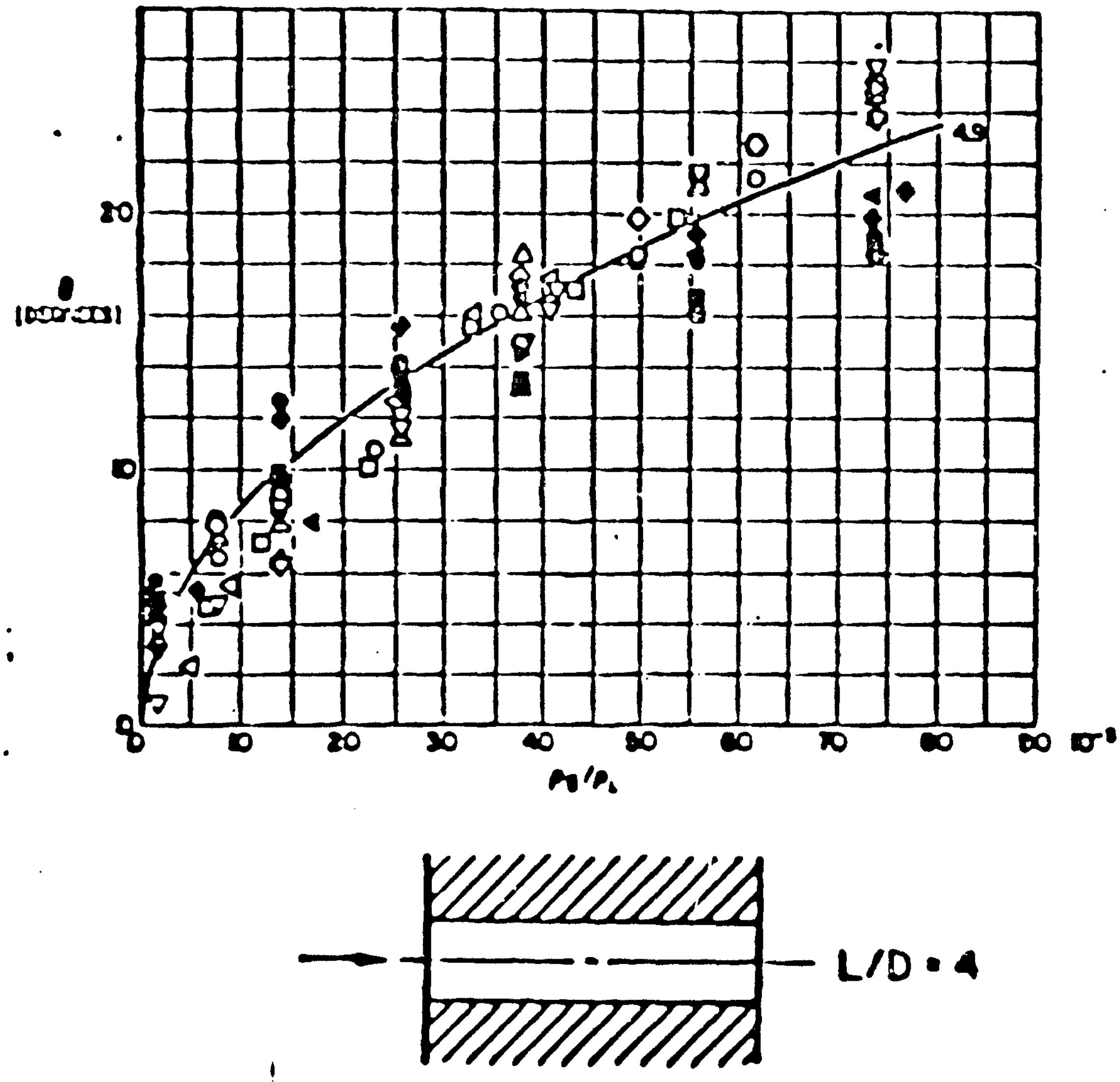
$$\omega^2 + 2\nu_1 k^2\omega\left(\frac{I_1'(ka)}{I_0(ka)} - \frac{2kl}{k^2+l^2}\frac{I_1(ka)}{I_0(ka)}\frac{I_1'(la)}{I_1(la)}\right)$$

$$= \frac{\sigma k}{\rho_1 a^2}(1 - a^2k^2)\left(\frac{l^2-k^2}{l^2+k^2}\right)\frac{I_1(ka)}{I_0(ka)}$$

$$+ \frac{\rho_2}{\rho_1}\left(U_0 - \frac{i\omega}{k}\right)^2 k^2\left(\frac{l^2-k^2}{l^2+k^2}\right)\frac{I_1(ka)K_0(ka)}{I_0(ka)K_1(ka)} \quad (3)$$

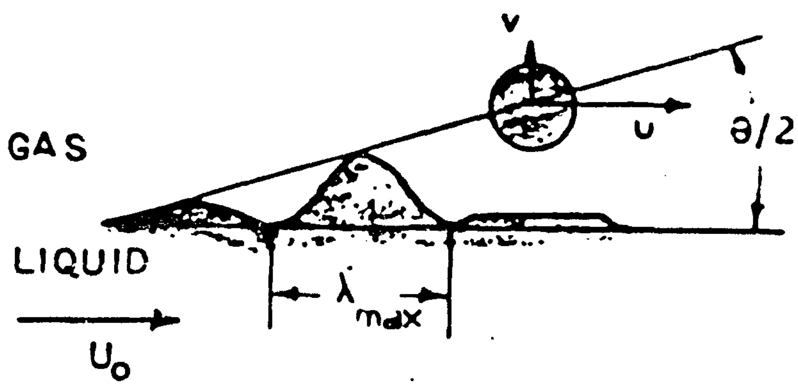


$$\tan\frac{\theta}{2} = \frac{v}{U_0} = \frac{1}{A}\frac{2\pi}{k_m}\frac{\omega_m}{U_0} = \frac{1}{A}4\pi\left(\frac{\rho_2}{\rho_1}\right)^{1/2} f(T)$$



Glycerol, Water, Hexane, Tetradecane
Different Nozzle Diameters: 254, 343, 610
Different Liquid Pressures: 500 to 13,300 psi
Different Gases: N_2, N_e, X_e, Air
Constant Temperature = 300°F

LIQUID INJECTION



$$\lambda_{max} = 2\pi x_{max}\, \sigma / \rho_g U_o^2$$

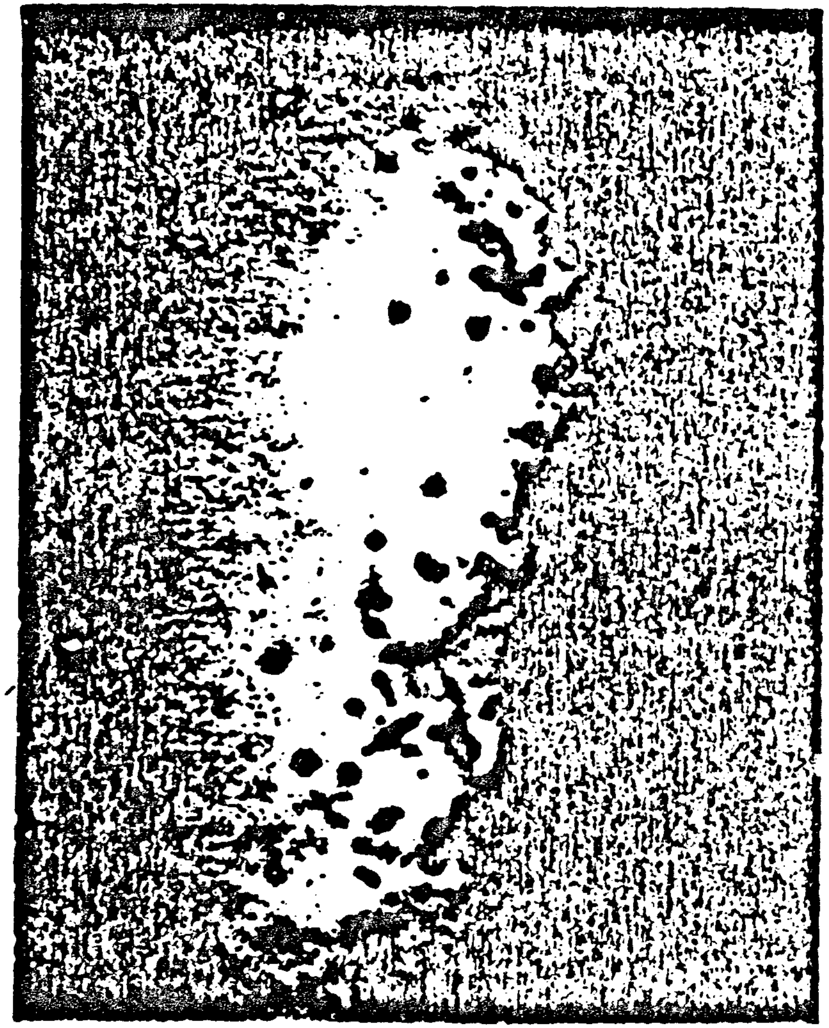
$$r_{drop} = \sqrt[3]{\frac{3}{8\pi A}}\; \lambda_{max}$$

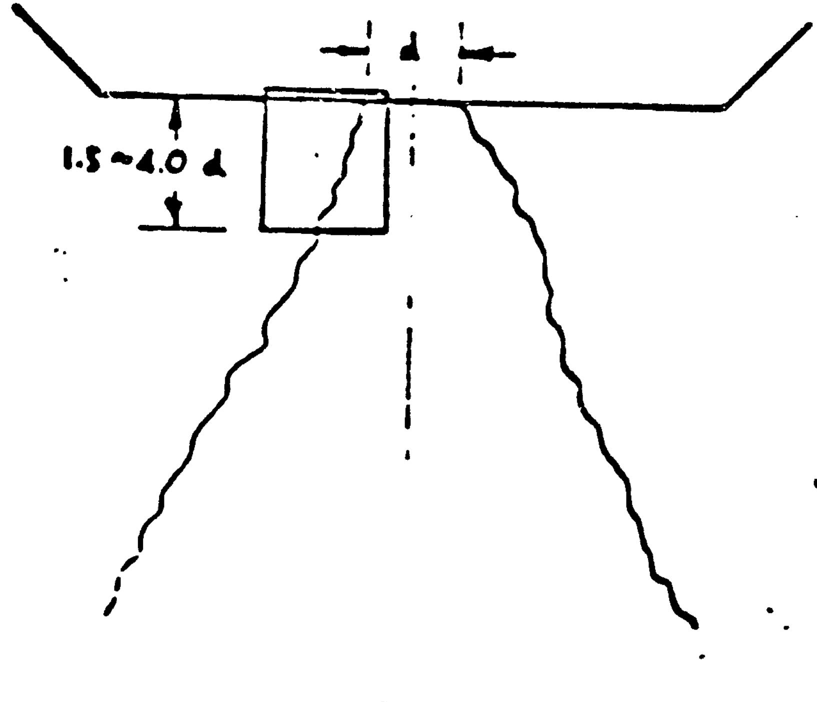
$$\tan \theta/2 = \frac{v}{u} = \frac{4\pi}{A}\sqrt{\frac{\rho_g}{\rho_l}} \cdot f\left(\frac{\rho_l}{\rho_g}\left(\frac{Re}{We}\right)^2\right)$$

$$\tau = \beta \lambda_{max} / U_o A \tan \theta/2$$

$$\beta = \frac{L_B}{D_{INJ}} \overline{\tan}\, \theta/2$$

$$N_{drops/l} = 2\pi R_{jet} / \lambda_{max}^2$$





Nozzle Diameter:
Field of View
Drop Velocity

	NOZZLE	LIQUID	$\rho_g \times 10^3$ g/cm^3	U_0 cm/ms	L_B/D_{inj}	SMR μ EXPERIMENT	ATOMIZE	MODEL
1	335-4	C_6H_{14}	17.0	5.94	140	5.4	0.94	2.4
2	"	"	32.9	5.24	100	5.6	0.64	2.9
3	"	"	17.0	7.92	140	4.4	0.55	1.6
4	"	"	32.9	9.28	83	4.9	0.22	2.0
5	"	"	17.0	9.90	123	3.2	0.36	1.2
6	"	"	32.9	11.10	77	3.4	0.16	1.8
7	335-10	"	17.0	7.92	140	4.7	0.57	1.9
8	127-4	"	"	5.86	140	4.1	0.97	2.9
9	335-4	$C_{14}H_{30}$	"	8.12	140	5.9	1.07	2.1

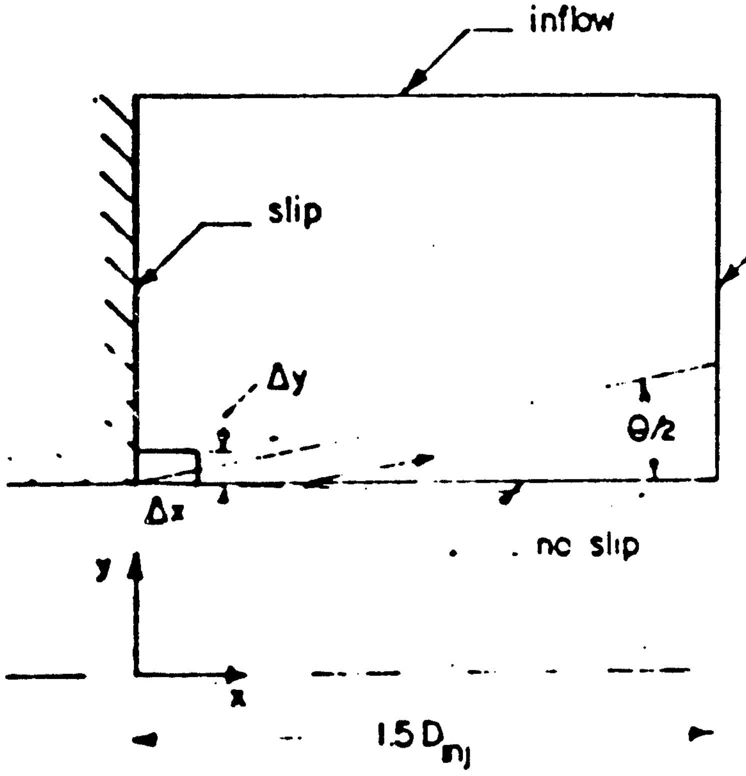
NOTE: L_B/D_{inj} From HIROYASU et al. 1982

$A = 5.2$ ($L/D = 4$) , $A = 4.6$ ($L/D = 10$)

SPRAY MODEL

1. STOCHASTIC PARCEL INJECTION
2. STOCHASTIC PARCEL COLLISION AND COALESCENCE
3. IMPLICIT COUPLING OF DROPS AND GAS
4. INCLUSION OF THE GAS VOLUME FRACTION EFFECT ON THE MASS MOMENTUM AND ENERGY TRANSFER RATES
5. INCLUSION OF TURBULENCE EFFECTS ON DROPS AND GAS

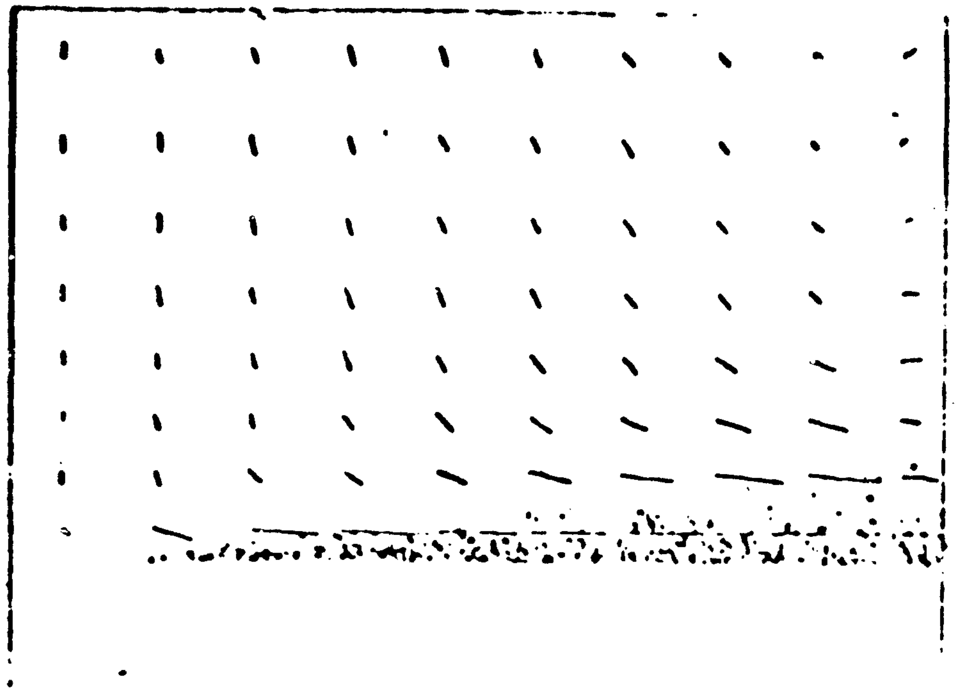
COMPUTATIONAL DOMAIN

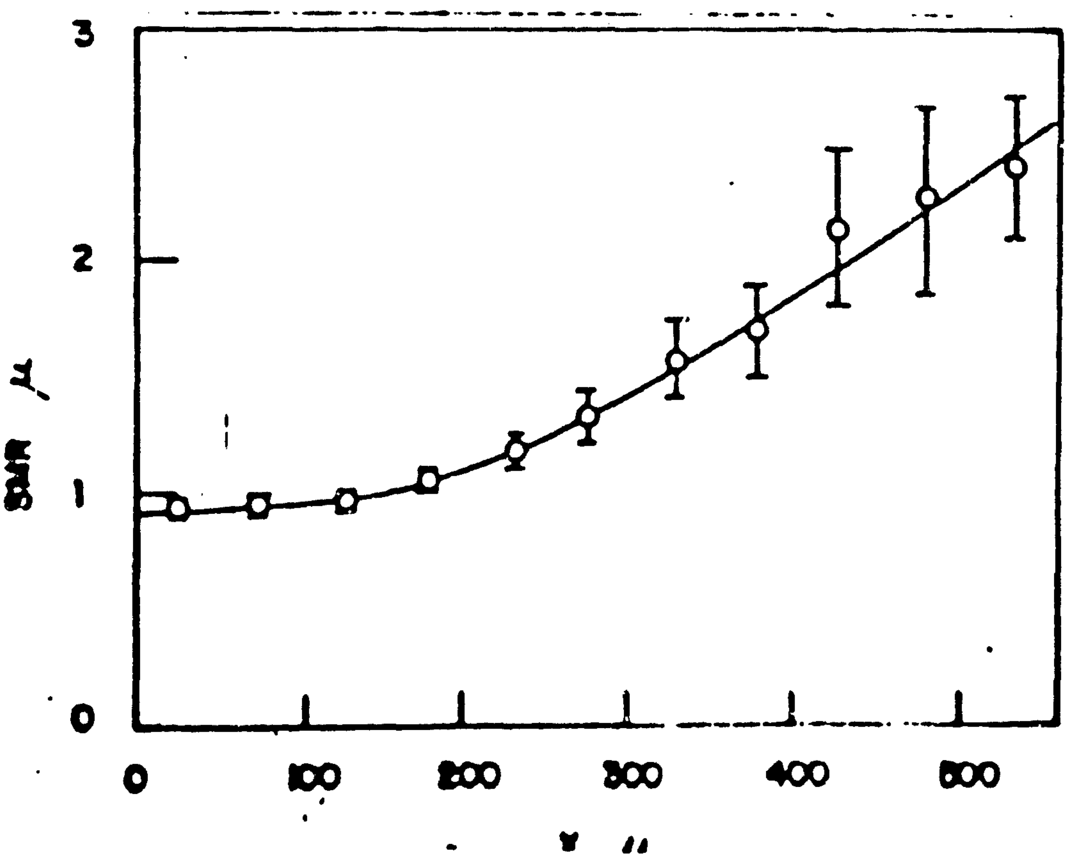


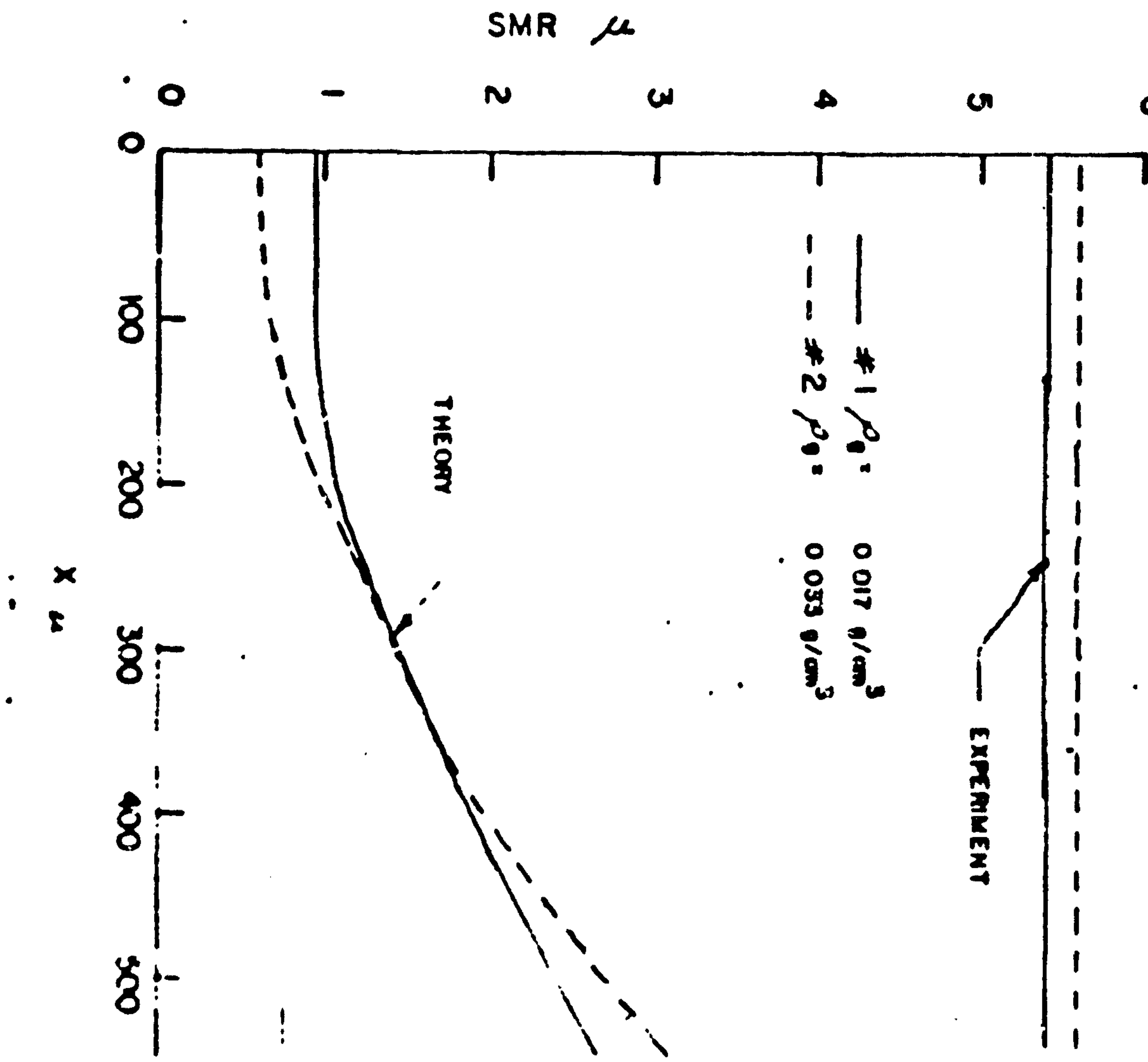
Δt = 0.05 - 0.25 μs
Δy = 30 μ + 10 %
Δx = 50 μ

ASSUMPTIONS

1. jet surface velocity = const. = U_0
2. surface regression negligible
3. mass flux = const
4. monodisperse drop size and velocities
5. surface saturated




3
2
1
0
0
100
200
300
400


SMR μ
0
1
2
3
4
5
6
0
100
200
300
400
500
X μ
#1 ρg = 0.017 g/cm³
#2 ρg = 0.033 g/cm³
THEORY
EXPERIMENT

CONCLUSIONS:

1. Measured trends of jet outer surface drop size vs injection velocity gas density, nozzle l/d and surface tension are modeled satisfactorily with the aerodynamic mechanism if droplet collision and coalescence is accounted for.

2. Additional studies are necessary to explain a.) trend with respect to nozzle diameter b.) predicted size lower than measured drop size.

3. Additional measurements are required probing the inner core of the jet before the atomization mechanism can be resolved fully.

APPENDIX E

Measurement Techniques

Figures by W. D. Bachalo

SPRAY MEASUREMENTS

METHODS AND APPLICATIONS

W .D. BACHALO

AEROMETRICS Inc.

P.O. BOX 308

MOUNTAIN VIEW, CA

OBJECTIVES

- **Discuss Spray Measurement Requirements**
- **Review Present Capabilities**
- **Initiate Discussion On Current And Future Research Goals**

DEFICIENCIES

IN EXISTING SPRAY DATA

- Reliability
- Simultaneous Size And Velocity Measurements
- Angle of Trajectory
- Drop Concentrations
- Gas Phase Measurements In Sprays
- Polydisperse Two-Phase Flow Measurements
- Drop Drag Coefficient
- Turbulent Drop Dispersion
- Spray Flame Measurements

AEROMETRICS, INC.

INTRODUCTION

The measurement of particle or drop size as well as velocity is needed in a number of applications associated with the laser Doppler velocimeter (LDV). It is well known that the particles used to scatter light must be small enough to adequately respond to the flow velocity fluctuations but large enough to scatter sufficient light intensities. A method for simultaneous measurement of the particle size and velocity can mitigate the concern with the particle generation by limiting the velocity measurements to the small particles. In other cases, fluid velocity measurements are required in the presence of a dispersed particle field. Such two-phase flow measurements may be associated with spray drops in a turbulent gaseous flow, solid particles in a slurry, or bubbles in cavitation studies. Several methods including signal amplitude discrimination have been used to limit the fluid velocity measurements to the small particles. However, these methods do not completely eliminate the signals from larger particles because of the Gaussian intensity distribution of the laser. A method is required that can perform simultanous measurements of the particle (or bubble) size over a large size range.

There is also a great deal of interest in measuring the size and velocity distributions of particles (drops, bubbles or solid spheres). Current interest in spray combustion research, for example, requires that these measurements be made in complex turbulent flow environments and often in the presence of flames. Other applications demand the determination of mass flow rate which also requires the measurement of drop velocity.

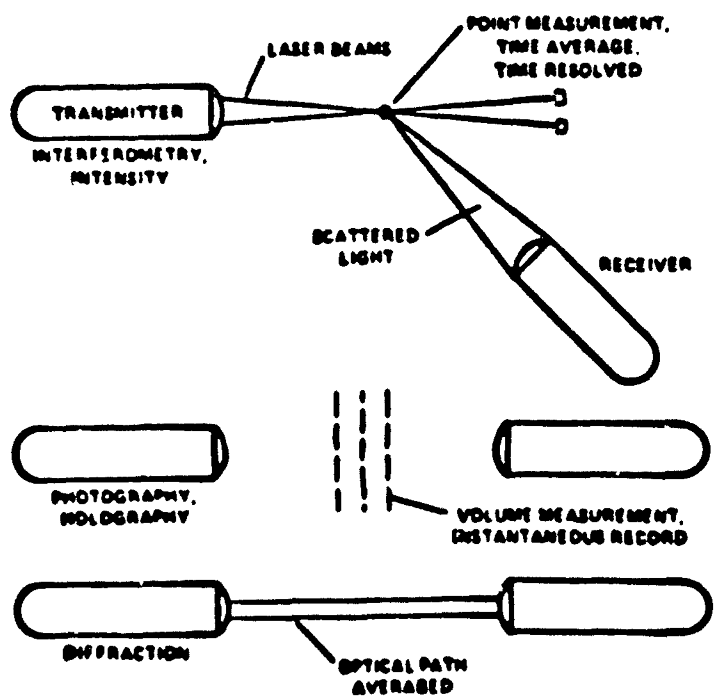
In this presentation, a new method for obtaining the aforementioned data will be described. The method referred to as the Phase/Doppler Particle Analyzer is similar to a standard laser Doppler velocimeter but has the added capability for measuring particle size. The presentation will cover the basic light scattering characteristics involved, the description of the method, its evaluation and examples of data obtained with the instrument.

General Comments On Particle Sizing

There are some general considerations to be made in selecting a particle sizing method. Perhaps the first is to assess the measurement requirements in terms of size range, working distances, spatial and temporal resolution, and whether the actual distribution or simply distribution parameters are measured. For example, the small angle forward scatter detection system measures the Sauter mean diameter (D_{32}) based on the average of the particles within the collimated beam path. Single particle counters measure the size of individual particles to produce a direct measurement of the size distribution. These measurements are made at points in the particle field. Imaging methods obtain size distributions over a volume of the particle field defined by the field of view and the depth of field. The size of the field of view as determined by the resolution requirements and the need to obtain an adequate statistical distribution with a reasonable number of recordings.

The type of sample averaging that occurs during the measurement may also be important. Modern small angle forward scatter diffraction systems and imaging systems can produce size distributions in an instant. That is, unsteady flows may be measured to obtain a time history of the spray size distribution. Single particle counters obtain size distributions that are average in time. Current systems obtain measurements at up to 50,000/sec. However, in unsteady flows an ensemble average taken over several cycles may be required. The Phase/Doppler Particle Analyzer (P/DPA) records the time of arrival of each measurement so the temporal behavior of the particle field can be reconstructed. Time resolved measurements are useful in Diesel sprays, for example, wherein the injection occurs in a short period of time but with change spray density and size distribution.

- SPATIAL AND TEMPORAL RESOLUTION
  - SPACE
    - POINT
    - PLANE OR VOLUME
    - OPTICAL PATH AVERAGE
  - TIME
    - INSTANTANEOUS
    - TIME AVERAGED
    - TIME RESOLVED
  - EXAMPLES



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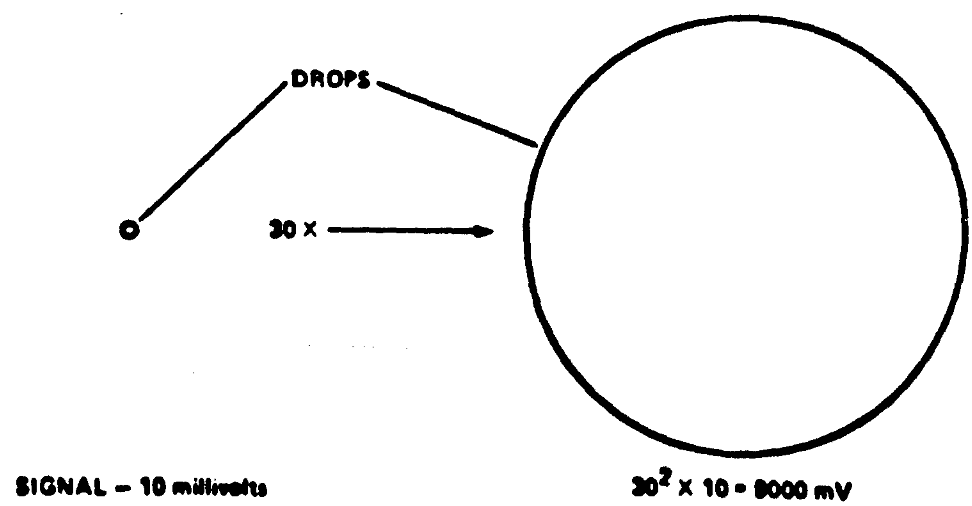
CONSIDERATIONS IN TECHNIQUE SELECTION

- MEASUREMENT CAPABILITY
  - LIMITS ON OVERALL SIZE RANGE
    - THEORETICAL - e.g. RESOLUTION LIMIT ON SMALL DROPS
    - ANALYTICAL DESCRIPTION - e.g. DIFFRACTION THEORY > 3μ
    - LOSS OF SENSITIVITY - e.g. DIFFRACTION BY LARGE DROPS IS CONCENTRATE IN THE FORWARD DIRECTION
  - DYNAMIC RANGE
    - MEASUREMENT RANGE AT ONE INSTRUMENT SETTING
    - LIMITATIONS
      - INSTRUMENT RESPONSE FUNCTION
      - DETECTOR/PREAMPLIFIER RESPONSE
      - SAMPLE VOLUME
      - LOSS OF SENSITIVITY
      - SIGNAL-TO-NOISE
      - OBSCURATION



SCHEMATIC ILLUSTRATING DROP SIZE RANGE AND SIGNAL RESPONSE

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Particle Number Density Considerations

Single particle counters have been recognized for their ability to obtain size distributions directly with high resolution and can be coupled with the LDV to obtain simultaneous measurements of size and velocity. However, the earlier arrangements using forward scattered light detection were severely limited by the need to have only a single drop in the sample volume at a time. Off-axis light scatter detection eliminated this problem.

The modern single particle counters can obtain measurements in sprays with very high number densities and are limited by similar conditions to the ensemble averaging techniques. The primary limit is the extinction of the laser beam. Measurements have been made with the beam extinction as large as 75%.

Multiple particle or ensemble detection methods (small angle forward scatter) are limited by the need to have a sufficient number of drops in the beam to produce an adequate signal-to-noise ratio. Single particle counters do not suffer from low number densities but the time required to obtain a distribution may become excessive. Well-designed instruments provide for very large changes in the sample volume to overcome this minor limitation.

The number density or particle flux is needed in many applications. Both the size and velocity are needed to accurately determine this parameter. In addition, the sample volume needs to be determined. This will be discussed in a later section. Ensemble methods cannot measure the particle number density directly. Often an extinction measurement is used to infer the number density.

- DROP NUMBER DENSITY $N(d)$
  - LIMITATIONS
    - SINGLE PARTICLE COUNTERS - ONE DROP IN SAMPLE VOLUME AT A TIME
    - MULTIPLE PARTICLE DETECTION - MANY PARTICLE NEEDED FOR SIGNAL-TO-NOISE
    - SAMPLE SIZE/SAMPLE VOLUME - SUFFICIENT NUMBER OF DROPS TO DETERMINE THE DISTRIBUTION
    - OBSCURATION
    - EXTINCTION
    - MULTIPLE SCATTERING
  - MEASUREMENT OF $N(d)$
    - SINGLE PARTICLE COUNTER
    - LIGHT EXTINCTION MEASUREMENT
    - COLLECTION OF DROPS

Size Distribution Type

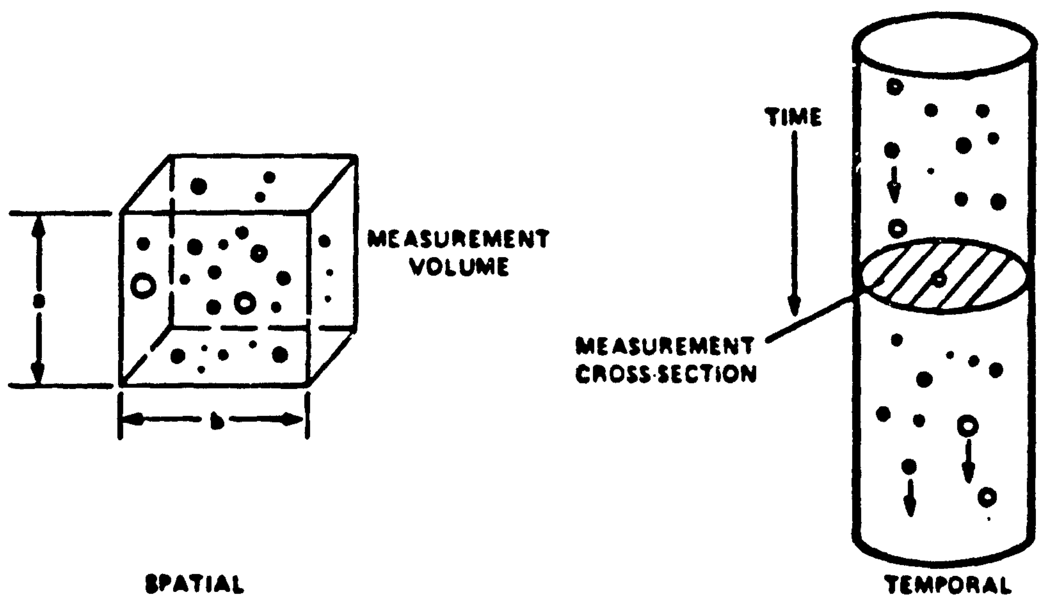
In particle field studies it is important to define and understand the differences between the types of distributions that are acquired. A spatial distribution is obtained when a collection of drops occupying a given volume of space is sampled instantaneously, as with a high-speed photographic or holographic means. As illustrated in the adjacent figure, the size distribution is sensitive to the relative number density of each size class, N(d) in particles per unit volume.

A temporal distribution is generated by measuring individual drops that pass through a sampling cross-section during an interval of time. Thus, temporal distributions are generally produced by collection techniques and by optical instruments which are capable of sensing individual particles. The temporal distribution depends upon the particle flux.

The temporal distribution may be transformed into the spatial by dividing the number of samples in each size class by the average velocity of the particles in that size class. If all of the drops are moving at the same velocity, the spatial and temporal distributions are identical. However, sprays generated by pressure atomizers, for example, will produce differences in velocity of an order of magnitude between the smallest to largest drops. This emphasizes the need for simultaneous drop size and velocity measurements.

- SIZE DISTRIBUTION TYPE
  - SPATIAL
    - AVERAGED OVER FINITE VOLUME
    - INSTANTANEOUS SAMPLE
    - SENSITIVE TO RELATIVE NUMBER DENSITY $N(d)$, PARTICLES/VOLUME
  - TEMPORAL
    - TIME AVERAGED
    - SENSITIVE TO PARTICLE FLUX

$$F = N(d_i)V(d_i)A(d_i)$$



SCHEMATIC OF DISTRIBUTION ACQUISITION

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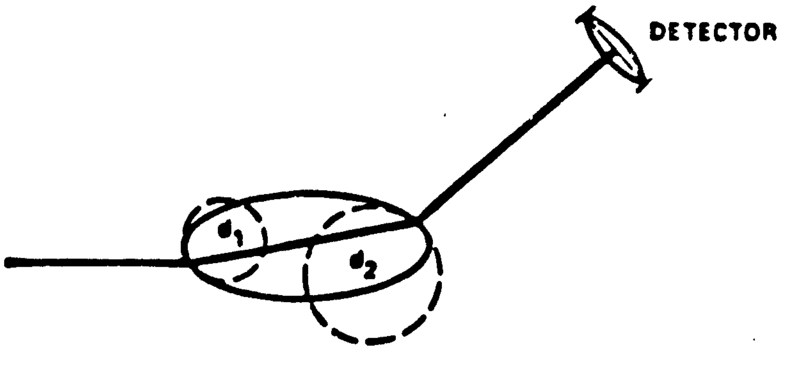
- DROP SHAPE
  - SENSITIVITY
  - DETECTABILITY
  - MEASUREMENT

- TECHNIQUES
  - IMAGING - PROJECTED DIAMETER, OR DIMENSIONS
  - DIFFRACTION - SAME AS ABOVE IF SYMMETRIC DETECTION
    - AVERAGES TO PROJECTED "DIAMETER"

– PROJECTED DIAMETER, OR DIMENSIONS

  - REFRACTION OR REFLECTION - SENSITIVE TO RADII OF CURVATURE
    - MEASURED DIAMETER AN "AVERAGE" OF d_1 AND d_2



– MEASURED DIAMETER AN "AVERAGE" OF d_1 AND d_2

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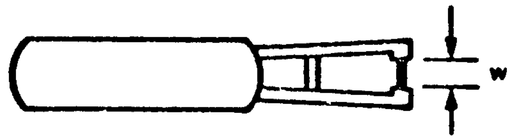
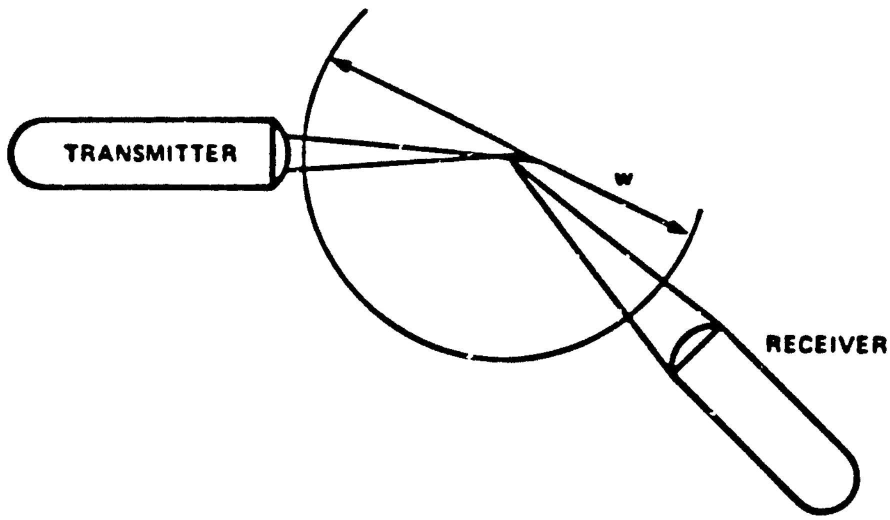
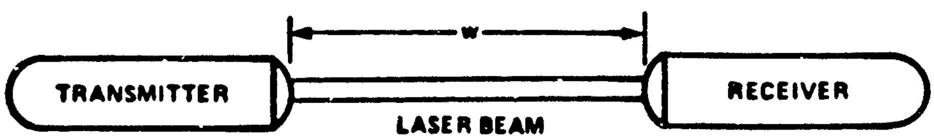
- COMPATIBILITY WITH TEST ENVIRONMENT
  - ACCESS REQUIREMENTS
  - WORKING DISTANCE, ω
  - INTRUSIVE OR NONINTRUSIVE
  - CONTAMINATION
  - LIGHT EXTINCTION
  - IMAGE DISTORTION



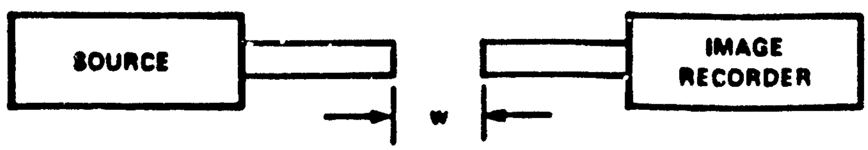
SCATTERED LIGHT DETECTION AND SHADOWGRAPH



SCATTERED LIGHT DETECTION AND INTERFEROMETRY



SMALL ANGLE FORWARD SCATTER DIFFRACTION



PHOTOGRAPHY AND HOLOGRAPHY

EXAMPLES OF MEASUREMENT TECHNIQUES SHOWING NONINTRUSIVE WORKING DISTANCES

- DROP COMPOSITION SENSITIVITY
  - INDEX OF REFRACTION
    - IMAGING, DIFFRACTION HAVE LITTLE OR NO DEPENDENCE
    - REFRACTION AND REFLECTION ARE DEPENDENT ON REFRACTIVE INDEX
    - INTERFEROMETRY CAN ELIMINATE DEPENDENCE
  - DENSITY - PRIMARILY FOR IMPACTORS
  - MULTICOMPONENT - SLURRIES, EMULSIONS
    - INTERNAL SCATTERING
    - IMAGING - OKAY
    - INTERFEROMETRY - OKAY IF REFLECTED LIGHT IS MEASURED
  - TEMPORAL AND SPATIAL VARIATIONS IN COMPOSITION
    - INDEX OF REFRACTION CHANGES AS VOLATILES EVAPORATE
    - SLURRY DROPS CHANGE IN MORPHOLOGY AS LIQUID EVAPORATES

SPRAY MEASUREMENTS

DIAGNOSTIC METHODS

- **Imaging**
- **Ensemble Light Scattering**
- **Single Particle Light Scattering**
- **Material Probes**

CATEGORIES OF TECHNIQUES

- IMAGING - "SEEING IS BELIEVING"
  - ADVANTAGES
    - EASY TO UNDERSTAND
    - INDEPENDENT OF DROP COMPOSITION
    - RECORDS DROP DISTRIBUTION IN SPACE
    - IDENTIFIED LIGAMENTS
    - DROP SHAPE MEASUREMENTS
  - DISADVANTAGES
    - SLOW DATA REDUCTION
    - SAMPLE SIZE LIMITED BY SAMPLE VOLUME AND NUMBER DENSITY
    - LIMITED WORKING DISTANCE, RESOLUTION
    - REQUIRES HIGH OPTICAL QUALITY
    - SAMPLE VOLUME FUNCTION OF DROP DIAMETER

- DIFFRACTION LIMITED RESOLUTION - ACTUAL RESOLUTION IS WORSE BECAUSE OF ABERRATIONS

$$R \simeq \frac{1.2\lambda S}{D}$$

S-LENS TO IMAGE DISTANCE
D- LENS DIAMETER

- DEPTH OF FIELD, L_i
  - HIGH RESOLUTION REQUIRES SHORT DEPTH OF FIELD

$$L_i = 2.4\lambda(S/D)^2 \text{ , } d = R$$

$$L_i \simeq 1.7R^2/\lambda$$

- MATERIAL PROBES - e.g. HOT-WIRE
  - ADVANTAGES
    - EASY TO USE
    - INEXPENSIVE
    - LARGE SIZE RANGE
  - DISADVANTAGES
    - INTRUSIVE/PERTURBING
    - LIMITED DROP SPEED/DROP SHATTERING
    - UNCERTAINTIES IN SAMPLE VOLUME
    - CONTAMINATION SENSITIVE
    - TEMPERATURE SENSITIVE
    - UNCERTAIN END EFFECTS ON WIRE SUPPORTS

Particle Sizing By Light Scatter Detection

There are several methods available for obtaining the particle size from the detection of scattered light. Perhaps the most obvious means involves the measurement of the amplitude or intensity of the scattered light. Particles greater than the light wavelength (~3 microns) scatter light in proportion to their diameter squared. The scattered intensity of known-sized particles can be measured to calibrate the system to determine the collection efficiency and gain before measuring size distributions.

When using laser beams, the Gaussian intensity distribution presents an ambiguity due to the uncertainty in the incident intensity on the particles. The random trajectories of the particles through the beam presents a range of incident intensities on the drops. One method used to remove this uncertainty is to accept only signals from particles that pass through the center of the beam. This may be done with a pair of detectors and specially designed masking systems. Unfortunately, the method requires a very short working distance.

Another method involves the use of two concentric beams, one with a much smaller diameter than the other and having a different wavelength or polarization. This "pointer beam" method uses the smaller beam to indicate when the particles have passed through the center of the larger beam. A deconvolution method has also been developed which uses statistical methods to resolve the ambiguity.

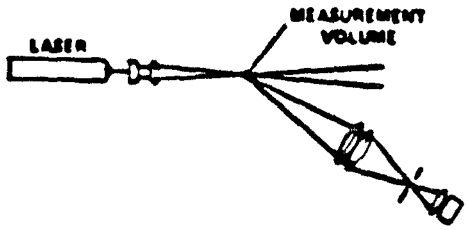
In general, scattering intensity methods require frequent calibrations, are subject to errors resulting from laser beam attenuation and improper alignment. High particle number densities found in sprays, for example, can produce beam extinctions as high as 70%. Refractive index fluctuations in spray flames can produce beam spreading and deflections. Each of these effects produces erroneous measurements resulting in size measurements that are too small.

In the forward scatter direction, the angular distribution of the scattered light is inversely proportional to the particle size. The angular distribution of the scattered light can be utilized to size particles from 0.1 to 300 micrometers in diameter. Small angle forward scattering (ensemble method) is used for particles in the size range of 5 to 300 micrometers with relatively good accuracy. For larger sizes the scattered light is concentrated along the transmitted beam and its measurement becomes very sensitive to the angular resolution of the detector.

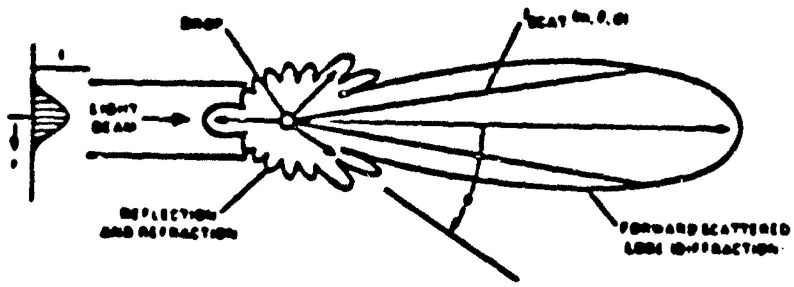
More recently, the theoretical description for the dual beam light scattering has been developed. The light scattering interferometry method bases the measurement of the particle size on the relative phase shift of light scattered from one beam with respect to the other. This method has the advantage of having a linear reponse to the particle size, is independent of the scattered intensity, and is easily combined with the laser Doppler velocimeter.

- LIGHT SCATTER DETECTION
  - POSSIBILITIES FOR SIZE DETERMINATIONS
    - SCATTERED LIGHT INTENSITY
    - ANGULAR DISTRIBUTION OF SCATTERED LIGHT
    - RELATIVE PHASE SHIFT OF SCATTERED LIGHT

- SCATTERED LIGHT INTENSITY
  - OPTICS



- SCHEMATIC OF LIGHT SCATTERING BY A SPHERE



- $I_{scat} = I_0 \frac{\pi d^2}{4} Q_{scat}(m, \theta, d)$

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Light Scattering Theory

Without going into details, the light scattered by homogeneous spherical particles of arbitray size is described exactly by the Lorenz-Mie theory. Unfortunately, this method is cumbersome for general use and is not amenable to gaining insights into the scattering phenomena. For very small particles ($d << \lambda$) the Rayleigh theory may be used as a good approximation. Light scattering by particles much larger than the light wavelength may be accurately described using geometrical optics theory. The diffraction and geometrical optics theories are asymptotic approximations to the Lorenz-Mie theory. These methods have the advantage of making it easy to understand the scattering mechanisms.

3.0 LIGHT SCATTERING THEORY

- RAYLEIGH SCATTERING ($d \ll \lambda$)
- LORENZ-MIE THEORY ($d \approx \lambda$)
  - HOMOGENEOUS SPHERES IN A HOMOGENEOUS ENVIRONMENT
  - VALID FOR SPHERES OF ARBITRARY SIZE
  - EXACT SOLUTION
- DIFFRACTION ($d \gg \lambda$)
  - APPROXIMATION HOLDS IF $\alpha = \frac{\pi d}{\lambda} > 20$
  - INDEPENDENT OF REFRACTIVE INDEX
  - AMPLITUDE PROPORTIONAL TO d^2
  - ANGULAR DISTRIBUTION PROPORTIONAL TO $1/d$
- GEOMETRICAL OPTICS - REFRACTION AND REFLECTION ($d \gg \lambda$)
  - APPROXIMATION HOLDS IF $\alpha = \frac{\pi d}{\lambda} > 50$
  - INDEX OF REFRACTION $\alpha(m-1) \gg 1$
  - AMPLITUDE PROPORTIONAL TO d^2
  - ANGULAR DISTRIBUTION INDEPENDENT OF d (AVERAGED OVER RESONANCES)

- ANALYTICAL DESCRIPTION OF THE SCATTERED LIGHT
  - SIZE PARAMETER $\alpha = \frac{\pi d}{\lambda}$
  - SCATTERED INTENSITY

$$i(\alpha, m, \theta) = |S(\alpha, m, \theta)|^2$$

$S(\alpha, m, \theta)$ – LIGHT SCATTERING AMPLITUDE FUNCTIONS

$i(\alpha, m, \theta)$ – SCATTERED INTENSITY COEFFICIENT

  - DIFFRACTION

$$S_{diff}(\alpha, \theta) = \alpha^2 \left[\frac{J_1(\alpha \sin \theta)}{\alpha \sin \theta}\right]$$

J_1 IS THE FIRST ORDER BESSEL'S FUNCTION OF THE FIRST KIND.

- COMMENTS
  - INTENSITY IS PROPORTIONAL TO d^2
  - d IS IN THE ARGUMENT OF $J_1(\alpha \sin \theta)$ (ANGULAR DEPENDENCE OF SCATTER DISTRIBUTION)
  - $I_{scat} = I_0 i(\alpha, m, \theta)$

    I_0 - INTENSITY INCIDENT UPON THE DROP

Geometrical Optics Theory

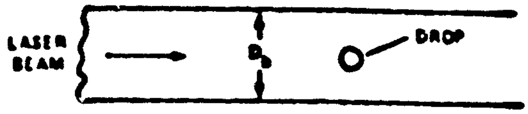
The geometrical optics description of light scattering is relatively simple. Laws of reflection and refraction are used to describe the direction and spread of the emergent light.

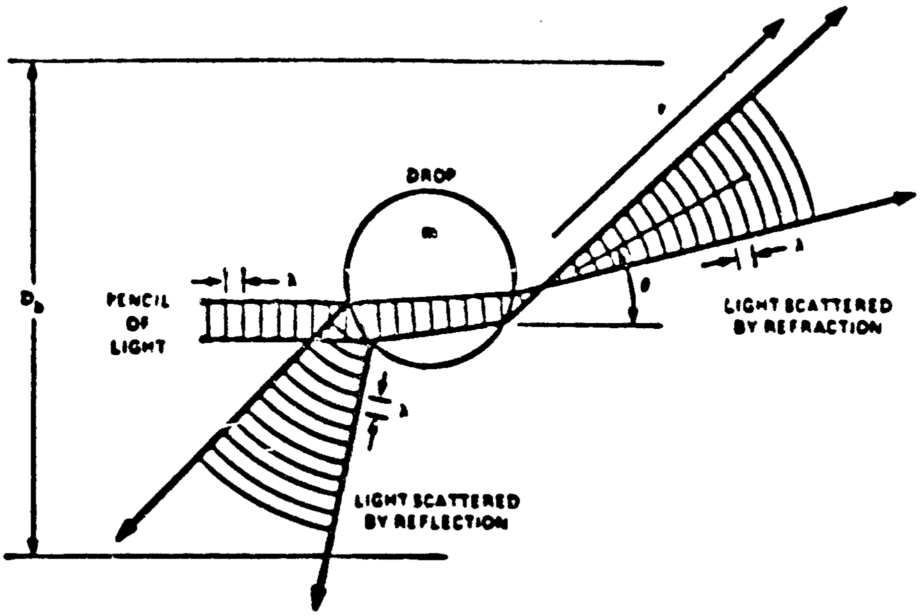
On the adjacent page a schematic of the light scattering phenomena is shown. A spherical particle is shown immersed in a laser beam. The lower enlarged figure shows a representative pencil of light incident on the sphere. Part of the light in the pencil is reflected and part is transmitted. The ratio in the two components can be determined from the Fresnel reflection coefficients. The light is deflected in accord with Snell's law and the laws of reflection.

Using these basic laws the scattering coefficients can be calculated and are shown on the following pages. The angle Θ is taken with respect to the transmitted laser beam. After obtaining the scattering amplitude coefficieints they are summed and the square of the amplitude is the intensity (remember that the amplitude coefficieints are complex numbers).

Plots of the scattering intensity obtained from the simple theories of diffraction, reflection and refraction are compared to the exact Lorenz-Mie theory calculations for a 5 micrometer sphere. The results including the high frequency resonances are in very good agreement.

- DRAWING SHOWING THE DROP IN THE LASER BEAM AND THE DIVERGENCE OF AN INCIDENT PENCIL OF LIGHT





EMERGENT LIGHT SPREADS INTO AN AREA

$$dA = r^2 \sin\theta \, d\theta \, d\phi$$

- REFLECTION (PERPENDICULAR POLARIZATION)

$$S_1^{(1)}(\alpha, m, \theta) = \alpha \frac{\sin\frac{\theta}{2} - \sqrt{m^2 - \cos^2\frac{\theta}{2}}}{\sin\frac{\theta}{2} + \sqrt{m^2 - \cos^2\frac{\theta}{2}}} \, \frac{1}{2} \exp\left[i\left(\frac{\pi}{2} + 2\alpha \sin\frac{\theta}{2}\right)\right]$$

- COMMENTS
  - α - DOES NOT AFFECT THE ANGULAR DISTRIBUTION EXCEPT THROUGH THE EXPONENTIAL PHASE TERM
  - SCATTERED INTENSITY IS DEPENDENT UPON REFRACTIVE INDEX m
  - EXPONENTIAL PHASE TERM IS INDEPENDENT OF THE REFRACTIVE INDEX

- REFRACTION (PERPENDICULAR POLARIZATION)

$$S_1^{(2)}(\alpha, m, \theta) = \alpha\left[1-\left(\frac{1+m^2-2m\cos\frac{\theta}{2}}{1-m^2}\right)^2\right]\sqrt{\frac{m^2\sin\frac{\theta}{2}\left(m\cos\frac{\theta}{2}-1\right)\left(m-\cos\frac{\theta}{2}\right)}{2\sin\theta\left(1+m^2-2m\cos\frac{\theta}{2}\right)^2}}$$

$$\times\exp\left[j\left(\frac{3\pi}{2}-2\alpha\sqrt{1+m^2-2m\cos\frac{\theta}{2}}\right)\right]$$

- COMMENTS
  - d DOES NOT AFFECT THE ANGULAR DISTRIBUTION (EXCEPT THROUGH THE EXPONENTIAL PHASE TERM)
  - SCATTERED INTENSITY IS DEPENDENT UPON REFRACTIVE INDEX, m
  - EXPONENTIAL PHASE TERM IS DEPENDENT UPON THE REFRACTIVE INDEX

- SCATTERED LIGHT INTENSITY

$$S(\alpha, m, \theta) = S_{diff}(\alpha, \theta) + S^{(1)}(\alpha, m, \theta) + S^{(2)}(\alpha, m, \theta)$$

$$i(\alpha, m, \theta) = |\, S(\alpha, m, \theta)\,|^2$$

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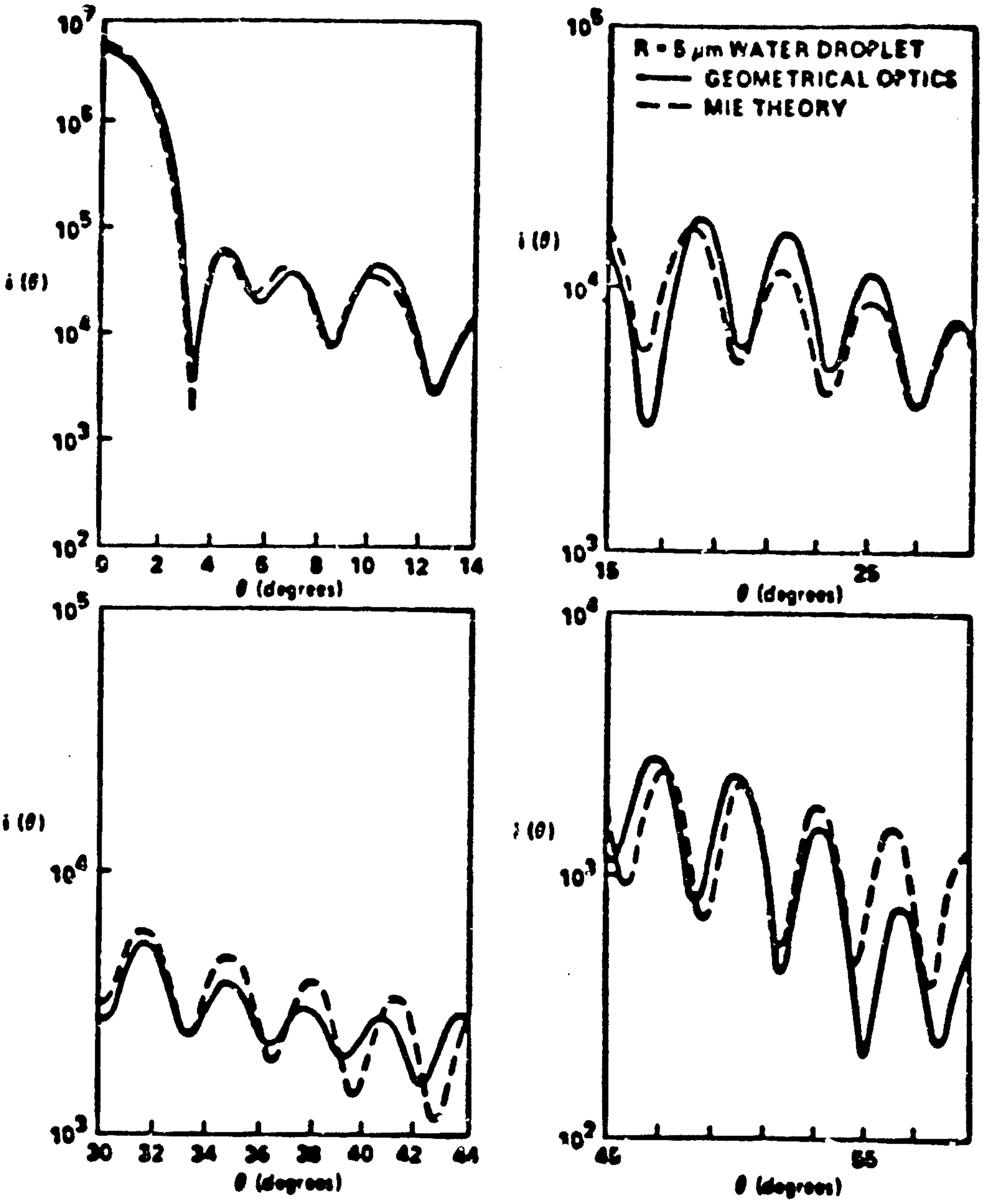
- EXAMPLE OF SCATTERING DIAGRAM



- COMMENTS:
  - GEOMETRICAL OPTICS IS IN GOOD AGREEMENT WITH EXACT MIE THEORY FOR 5μm DROP, $\alpha = \frac{2\pi r}{\lambda} \simeq 25$
  - OSCILLATIONS IN THE INTENSITY IS DUE TO INTERFERENCE BETWEEN THE SCATTERING MECHANISMS (REFRACTION, REFLECTION, AND DIFFRACTION)

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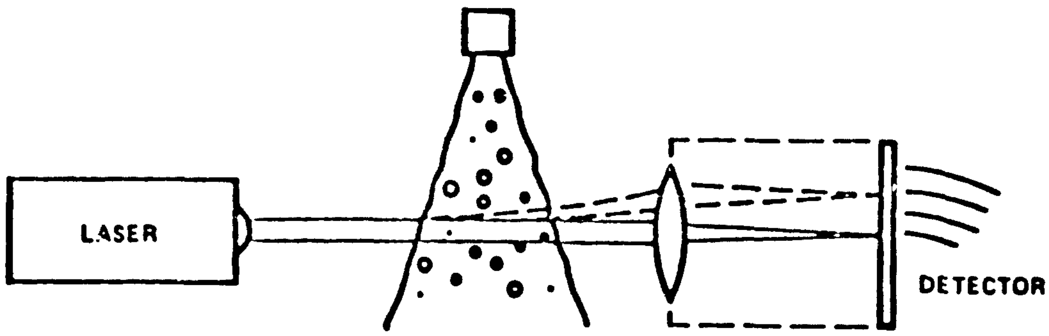
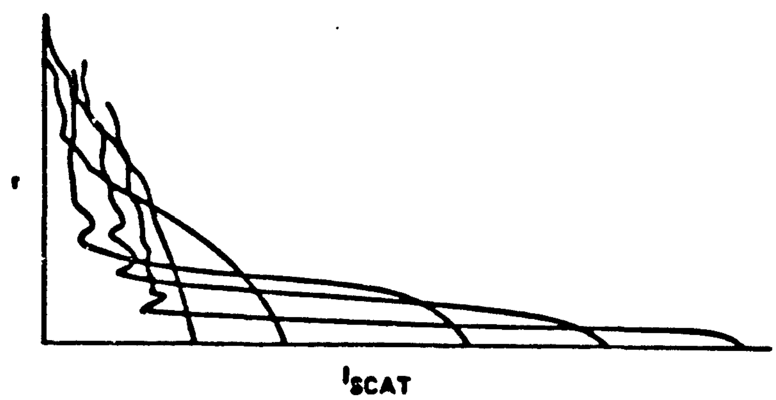
- **COMMENTS**
  - **INCIDENT LASER LIGHT, I_0, HAS GAUSSIAN INTENSITY DISTRIBUTION**
  - **INCIDENT INTENSITY ON DROP DEPENDS ON TRAJECTORY THROUGH BEAM**
- FORWARD SCATTERED LOBE - DIFFRACTION
  - AMPLITUDE PROPORTIONAL TO d^2
  - ANGULAR DISTRIBUTION PROPORTIONAL TO $1/d$
  - INDEPENDENT OF PARTICLE COMPOSITION

- "OFF-AXIS" SCATTERED LIGHT - REFLECTION AND REFRACTION
  - AMPLITUDE PROPORTIONAL TO d^2
  - ANGULAR DISTRIBUTION (AVERAGED) INDEPENDENT OF d
  - DEPENDS ON REFRACTIVE INDEX

- ANGULAR DISTRIBUTION OF SCATTERED LIGHT
  - SMALL ANGLE FORWARD SCATTER DETECTION
  - OPTICS





- SCHEMATIC DIAGRAM OF ENSEMBLE OF SCATTERED LIGHT INTENSITY DISTRIBUTIONS
  - COMMENTS
    - AVERAGE OF ALL PARTICLES IN THE BEAM DURING SAMPLE ACQUISITION
    - SENSITIVE TO ANGULAR DISTRIBUTION OF LIGHT (PROPORTIONAL TO $1/d$)
    - DECREASING RESOLUTION WITH INCREASE IN PARTICLE DIAMETER

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SINGLE PARTICLE COUNTERS

- **Intensity**
- **Relative Phase Angle**

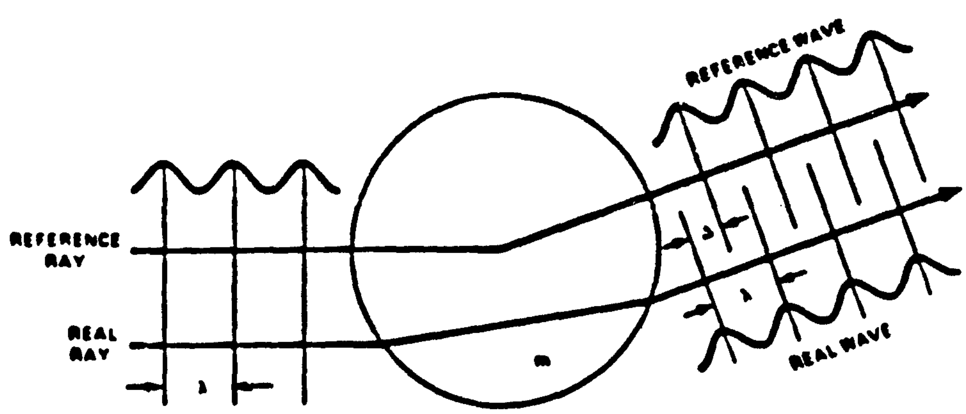
COMMENTS ON LIGHT SCATTER DECONVOLUTION METHOD

- **Sensitive To Beam Attenuation**
- **Alignment Is Critical**
- **No Size-Velocity Correlations**
- **Poor Sensitivity To Larger Drops With Near-Forward Scatter Detection**
- **Not Evaluated In Dense Sprays**

Light Scattering Interferometry

The phase of the light transmitted or reflected from the spherical particle is the key information used in the Phase/Doppler method. Relative phase shifts are introduced to the light wave as a result of the optical path differences of the rays scattered by the sphere. The adjoining figure shows a transmitted ray along with the imaginary reference ray deflected at the center of the sphere as if the sphere was not present. The relationship for the phase shift between the actual and reference rays is given. The τ and τ' are incident and refracted angles taken with respect to the surface tangent. p is the ray of interest (p = o first surface reflection, p = 1 single transmission, p = 2 internal reflection, etc.).

- PHASE SHIFT DUE TO LENGTH OF OPTICAL PATH



Δ = phase shift

$\Delta = \frac{2\pi d}{\lambda}(\sin\tau - pm\sin\tau')$

d = drop diameter

λ = light wavelength

ϕ = taken with respect to an imaginary ray deflected at the center of the sphere

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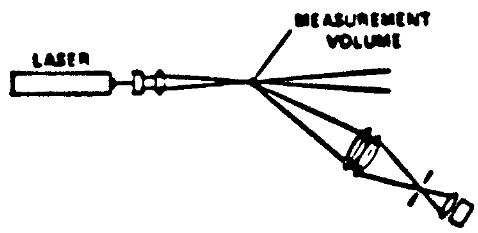
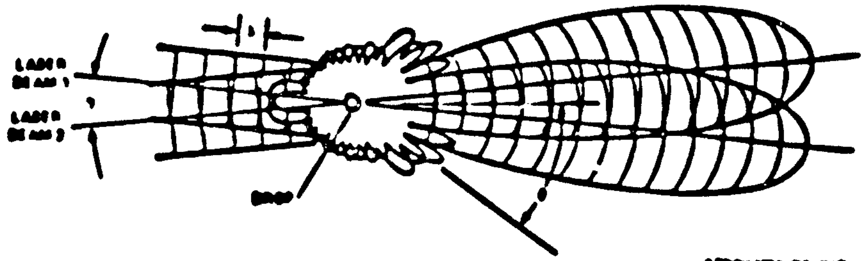
The light scattering interferometry method requires the same treansmitter optics as a dual beam LDV. When two intersecting beams are incident upon a particle, the particle scatters light from each beam independently.

If a representative ray from each beam is considered, it is easy to see that they reach a point P by different optical paths. This is true because they enter the sphere at different angles. The optical path difference results in a relative phase shift between the rays arriving at point P. The relative phase difference can be computed from the relationship described earlier. If the computations are carried out for each ray incident upon the sphere, a scattered interference fringe pattern can be generated.

• OPTICS



• SCHEMATIC OF DUAL BEAM LIGHT SCATTERING



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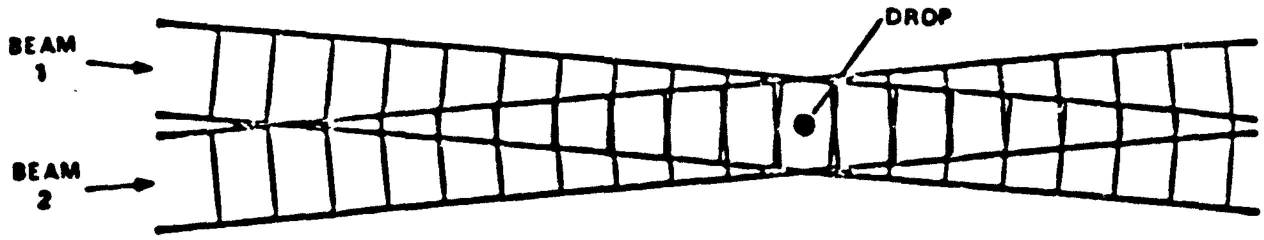
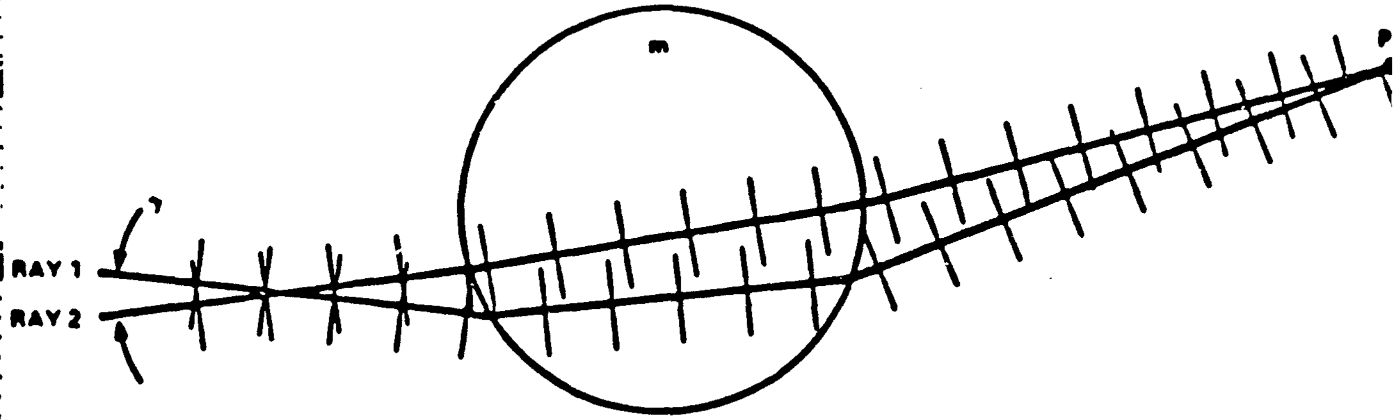
- TWO INTERSECTING LASER BEAMS INCIDENT UPON THE DROP





- OBSERVATIONS
  - RAYS FROM BEAMS 1 AND 2 REACH A COMMON POINT P BY DIFFERENT OPTICAL PATHS THAT DEPEND ON THE BEAM INTERSECTION ANGLE, γ AS WELL AS REFRACTIVE INDEX, m
  - THE OPTICAL PATH DIFFERENCE PRODUCES A RELATIVE PHASE SHIFT AT P

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- PHASE DIFFERENCE BETWEEN RAY 1 AND RAY 2 FROM BEAMS 1 AND 2
  -

$$\phi = \Delta_1 - \Delta_2$$

$$\phi = \frac{2\pi d}{\lambda}\left[(\sin r_1 - \sin r_2) - pm(\sin r_1' - \sin r_2')\right]$$

  - PRODUCES AN INTERFERENCE FRINGE PATTERN

- COMMENTS
  - PHASE ϕ IS PROPORTIONAL TO THE DROP DIAMETER, d
  - MEASUREMENT OF ϕ IMPLIES MEASURING THE INTERFERENCE FRINGE PATTERN
  - THE INTERFERENCE FRINGE PATTERN PRODUCED BY A MOVING DROP APPEARS TO MOVE AT THE DOPPLER DIFFERENCE FREQUENCY.

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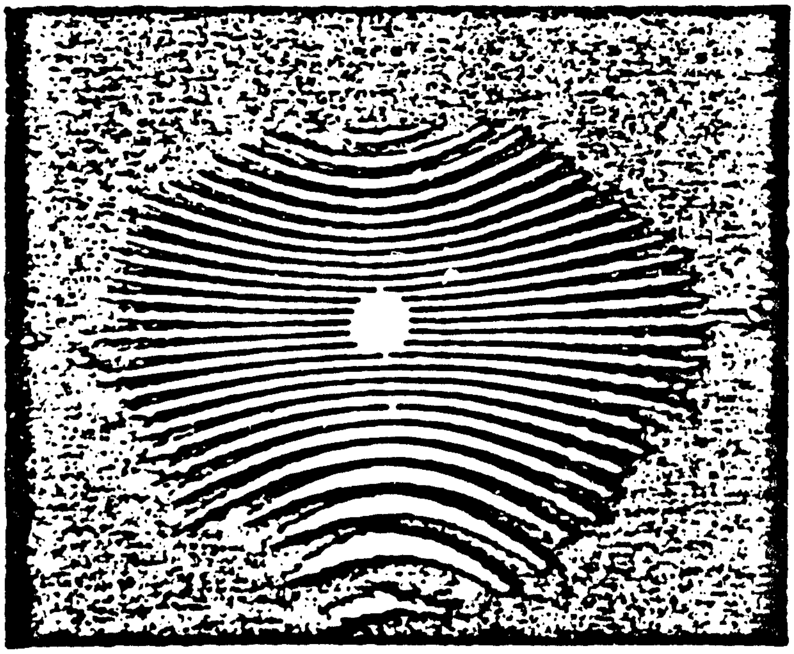
• PHOTOGRAPH OF THE SCATTERED INTERFERENCE FRINGE PATTERN

A photograph of the actual interference fringe pattern is shown. The fringe pattern was produced by a stationary drop held at the beam intersection. Note that the fringes are hyperbolic curves with straight fringes through the bisector of the beams. The spacing of the fringe pattern is inversely proportional to the drop size and also depends on where the observation is made. The theoretical predictions provide all of the necessary parametric information for obtaining the drop size.



Phase/Doppler Particle Analyzer

In order to obtain drop size measurements, the spacing of the interference fringes must be measured accurately. Particles moving through the laser beam intersection scatter interference fringes that move at the Doppler difference frequency. The laser Doppler velocimeter measures this frequency to obtain the particle velocity. A means is required to measure the fringe spacing at the same time.

If pairs of detectors are located in the field of the scattered fringe pattern, each detector will produce a Doppler burst signal but with a relative phase shift between the signals. The phase shift between the Doppler burst signals is inversely proportional to the fringe spacing and hence, directly proportional to the particle size.

Three detectors are required to avoid ambiguities associated with phase angle measurement of greater than 360°. The additional phase measurements also serve to extend the size range of the instrument at one optical setting. In addition, comparisons of the phase angle measurements between pairs of detectors are used to evaluate the measurements and to reject spurious signals.

- **OBSERVATIONS**
  - **TEMPORAL FREQUENCY OF THE SCATTERED FRINGE PATTERN IS LINEARLY RELATED TO PARTICLE VELOCITY - e.g. LASER DOPPLER VELOCIMETER**

$$\text{Velocity} = \delta \times f_D$$

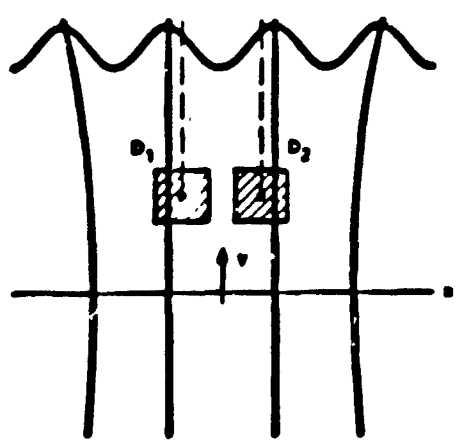
$$\delta = \frac{\lambda}{2 \sin \gamma/2} \quad - \gamma \text{ BEAM INTERSECTION ANGLE}$$

f_D – DOPPLER DIFFERENCE FREQUENCY

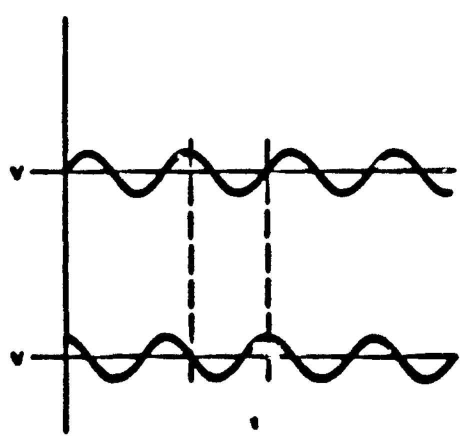
  - **SPATIAL FREQUENCY OF THE SCATTERED FRINGE PATTERN IS LINEARLY RELATED TO PARTICLE (SPHERE) DIAMETER**

$$\Delta = \frac{\pi d}{\lambda}\left[(\sin \gamma_1 - \sin \gamma_2) - pm(\sin \gamma_1' - \sin \gamma_2')\right]$$

- **PRINCIPLE OF MEASUREMENT - PAIRS OF DETECTORS LOCATED IN THE FIELD OF THE SCATTERED FRINGE PATTERN WILL PRODUCE SIMILAR DOPPLER BURST SIGNALS BUT WITH A PHASE SHIFT. THE PHASE ANGLE BETWEEN THE SIGNAL PAIRS IS PROPORTIONAL TO THE DETECTOR SPACING AND THE SCATTERED FRINGE SPACING.**

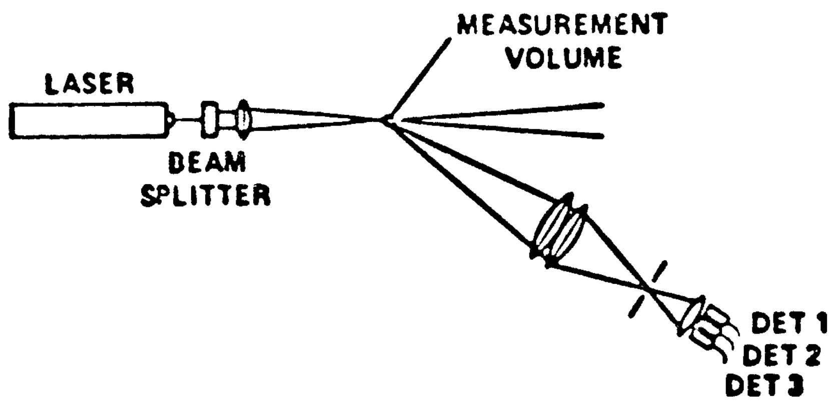


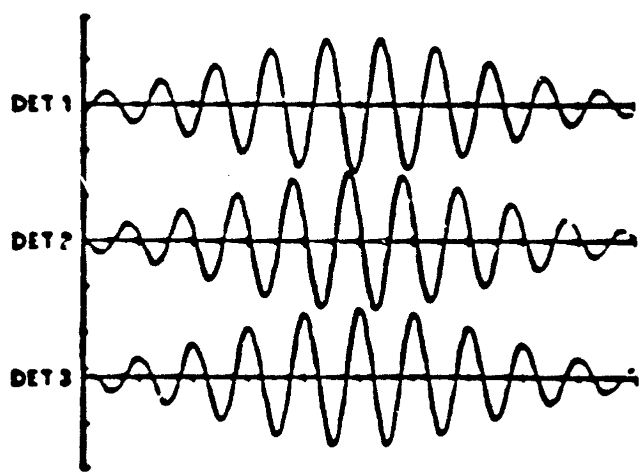
FRINGE PATTERN WITH DETECTOR APERTURES SHOWN



FILTERED SIGNALS

• OPTICAL SYSTEM





FILTERED DOPPLER BURST SIGNALS

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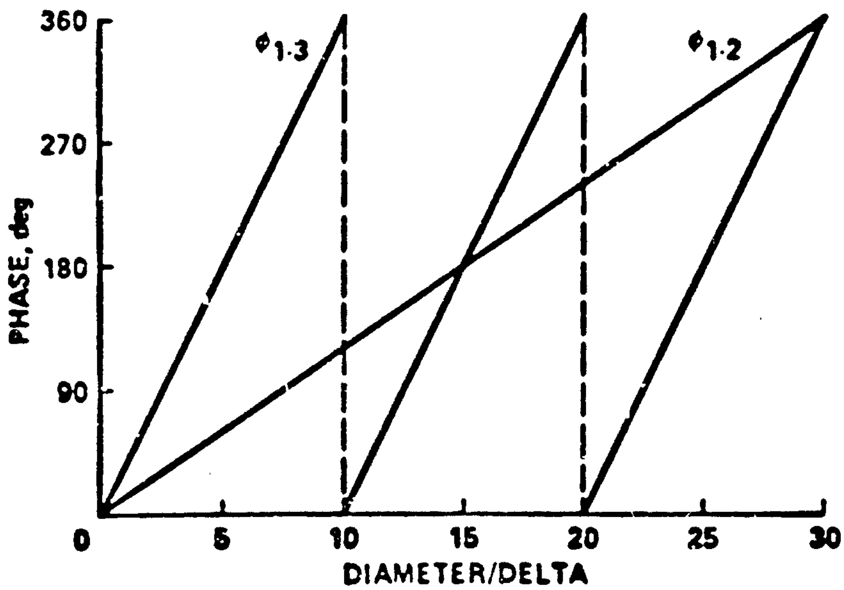
Phase Variation With Drop Size

The theoretical prediction of the phase angle versus the dimensionless drop size is shown on the adjacent figure. The line with the steeper slope identified as ϕ_{1-3} corresponds to the detectors with the greatest spacing while the lower slope of ϕ_{1-2} corresponds to the smaller detector spacing. In this particular example the ratio of the detector spacings was three. With this detector arrangement, the signal processor has sufficient resolution to provide a size range of 105 at a single optical setting.

The relationships for all of the optical parameters involved were tested using monodispersed drops. In all cases, the monodisperse drops could be measured to within a few percent of the predicted size.

- THEORETICAL ANALYSIS
  - PROVIDE MATHEMATICAL DESCRIPTION OF INTERFERENCE PATTERN
  - DEFINE PARAMETRIC EFFECTS
  - PRODUCE FUNCTIONAL RELATIONSHIP FOR DROP SIZE
  - DESCRIBE THE SAMPLE VOLUME AS A FUNCTION OF DROP SIZE

- THEORETICAL PREDICTION SHOWING THE PHASE VARIATION WITH DIMENSIONLESS DROP SIZE



INSTRUMENT RESPONSE CURVES

- COMMENTS
  - LINEAR RELATIONSHIP

$$\text{Delta} - \delta = \frac{\lambda}{2 \sin \gamma/2}$$

γ – LASER BEAM INTERSECTION ANGLE

  - THREE OR MORE DETECTORS REQUIRED TO:
    - PREVENT PHASE AMBIGUITY
    - INCREASE DYNAMIC RANGE AND MAINTAIN SENSITIVITY
    - REJECT SPURIOUS SIGNALS
    - DETERMINE DIRECTION OF FRINGE MOTIONS

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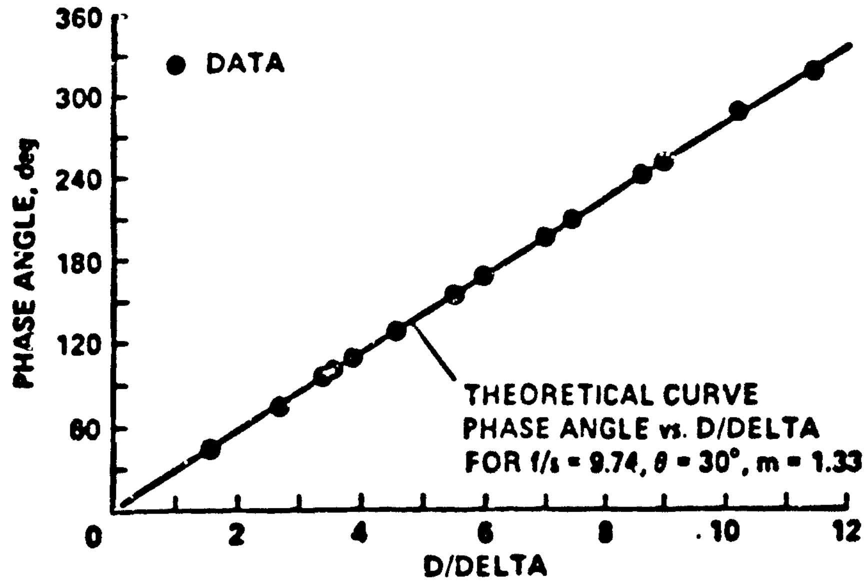
• VERIFICATIONS OF THE THEORETICAL PREDICTIONS



• SIZE RANGE SELECTION
  • BEAM INTERSECTION ANGLE
  • DETECTOR SPACING

• OPTICAL PARAMETERS AFFECTING MEASUREMENT

m - refractive index of drop
λ - laser light wavelength
γ - laser beam intersection angle
θ - observation angle
R - observation distance
S - detector spacing

• PARAMETERS CHANGE THE SLOPE (SIZE SCALE) OF THE RESPONSE CURVE

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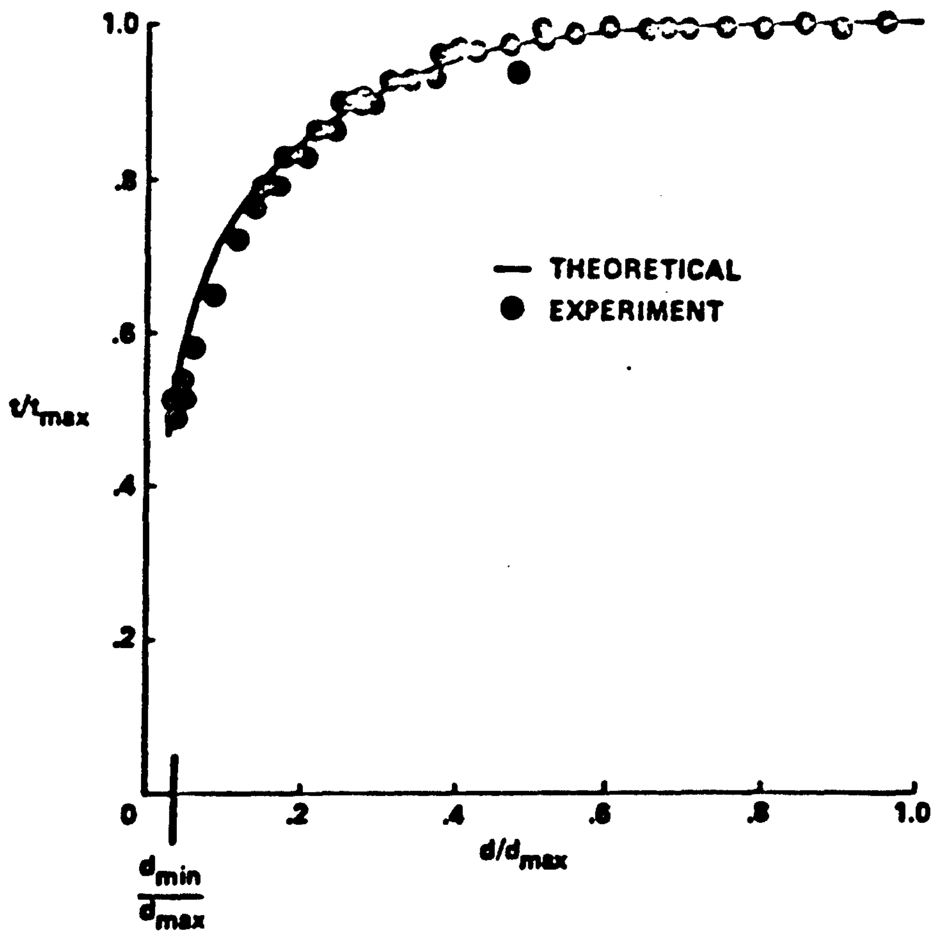
Sample Volume Normalizations

All single particle counters using lasers produce distributions that are biased due to the Gaussian beam intensity distribution. The bias occurs as a result of the larger particles producing a detectable signal from a larger area of the sample volume than the small particles. Small particles may only be detected when they pass through the central high intensity region of the beam.

The bias may be removed by accounting for the change in sampling cross-section with particle size. Analytical descriptions have been used by assuming an ideal Guaussian beam intensity distribution and that the beam intensity is not affected by windows or the particle field. This obviously cannot be relied upon in most practical applications.

The Phase/Doppler Particle Analyzer has incorporated a method for measuring the sample volume cross-section for each size class. Since the sample volume is measured with every size distribution, the effects of the measurement environment are accounted for in the sampling statistics. This method also provides greater confidence in the determination of the mass flowrate.

PROBE VOLUME CORRECTION FOR GAUSSIAN BEAMS



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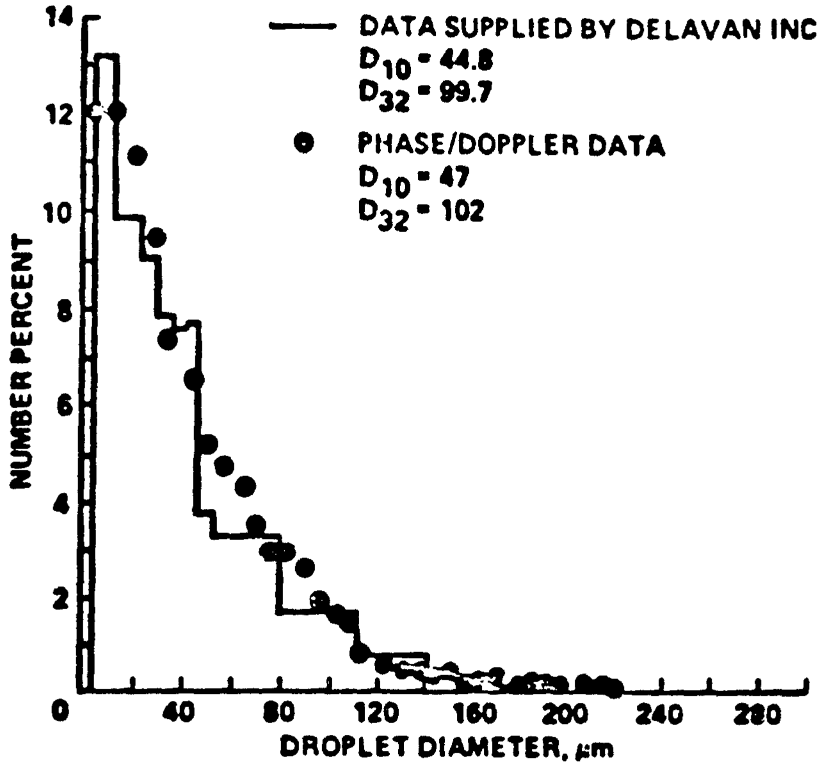
System Evaluation

Extensive experimentation was conducted to verify the performance of the P/DPA. The early experiments involved the measurement of monodisperse droplets with the beams passing through sprays. The spray had little or no affect on the measurements. Comparisons of spray measurements were made with other instruments. The adjoining figure shows an example of results obtained by Delavan Inc. These data were obtained using a light scattering probe for the small particles and an imaging system for the larger particles. The relatively large dynamic range of the P/DPA allowed the coverage of the entire size distirbution at one optical setting.

Other measurements were made to characterize the axial and radial size distributions of pressure and two-fluid atomizers. Representative results are shown on the attached figures. Note that the white dots within the histogram bars represent the data before being corrected for the effects of the Gaussian beam.

Size-velocity correlation data are also presented. These data represent the mean and rms velocities for each particle size class. The evolution of the spray as a result of the relative velocities of the particles and their respective rates of relaxation can be derived from these data. For example, the size velocity correlations have been presented to show the spray development with axial and radial distance.

- PRESSURE ATOMIZER
  - DELAVAN 45B, .6gph AT 60 psig
  - MODERATE DROP NUMBER DENSITY



PRESSURE ATOMIZER

- COMMENTS
  - COMPARISON TO DELAVAN INC MEASUREMENT
  - AGREEMENT ON D_{10} AND D_{32}
  - CANNOT CONCLUDE ACCURACY FROM D_{32} COMPARISON
  - SIZE DISTRIBUTION GREATER THAN FACTOR OF 30

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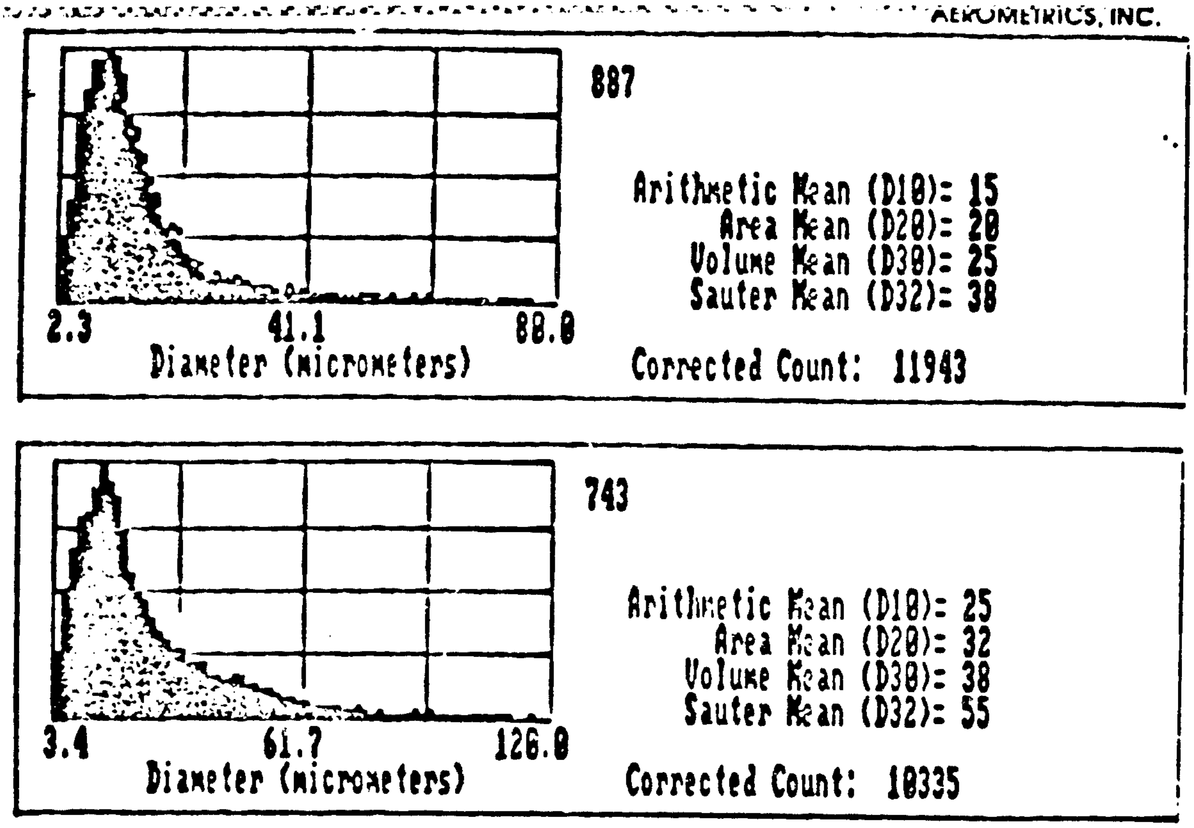
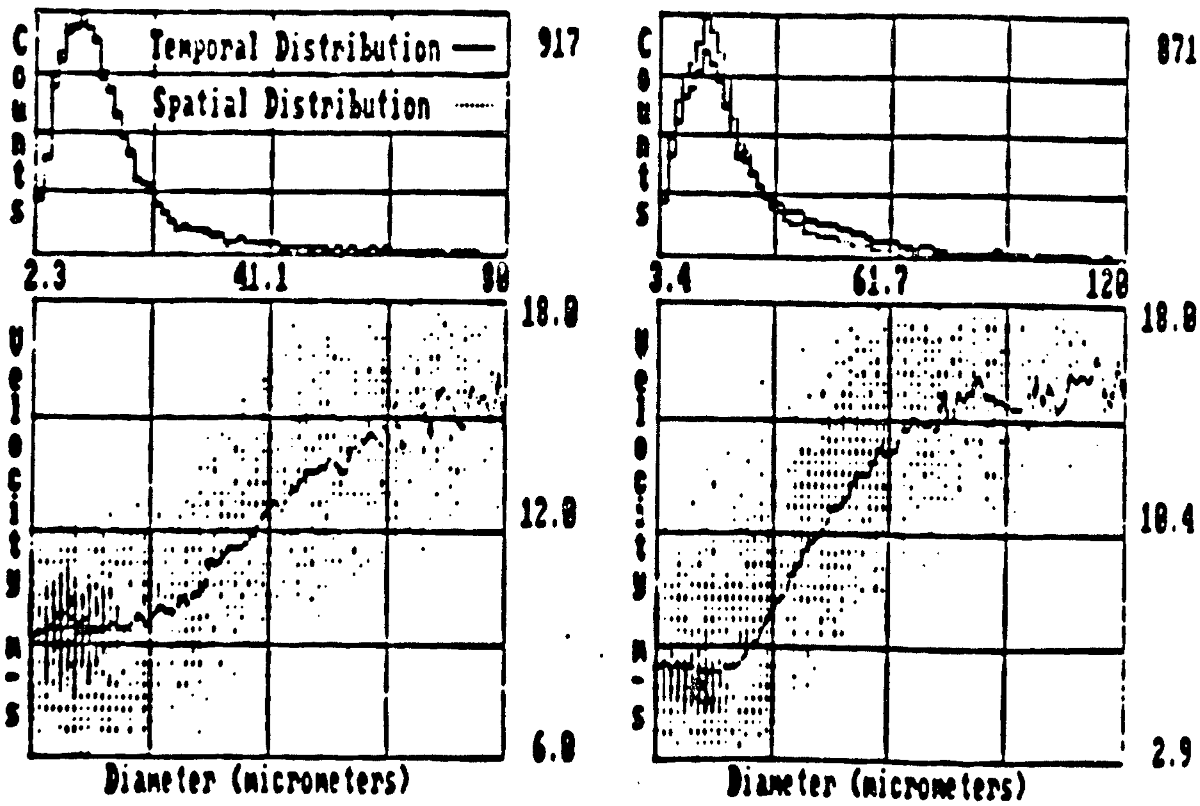
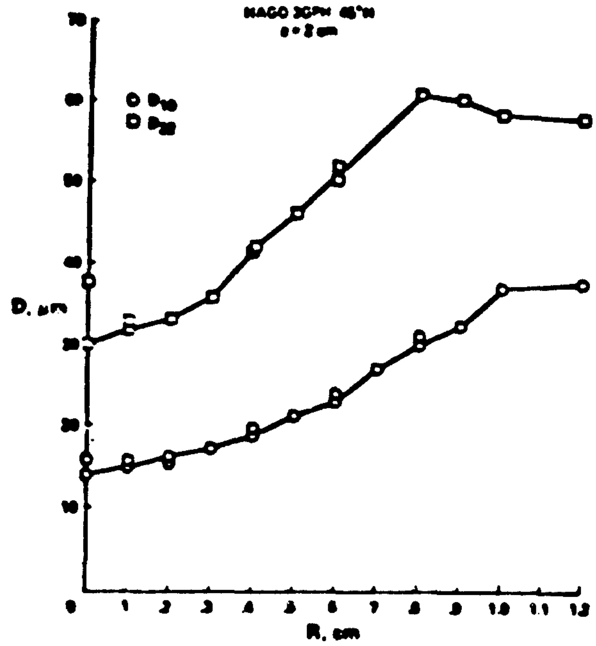


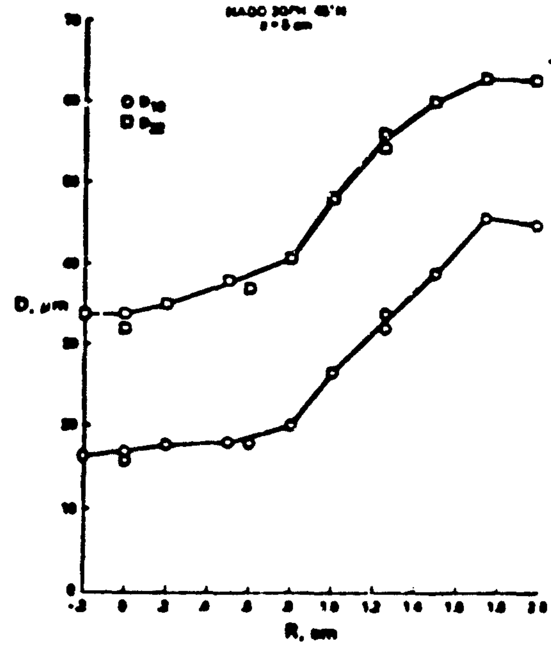
Drop Size Distribution



Temporal and Spatial Size Distributions with Corresponding Size - Velocity Correlations

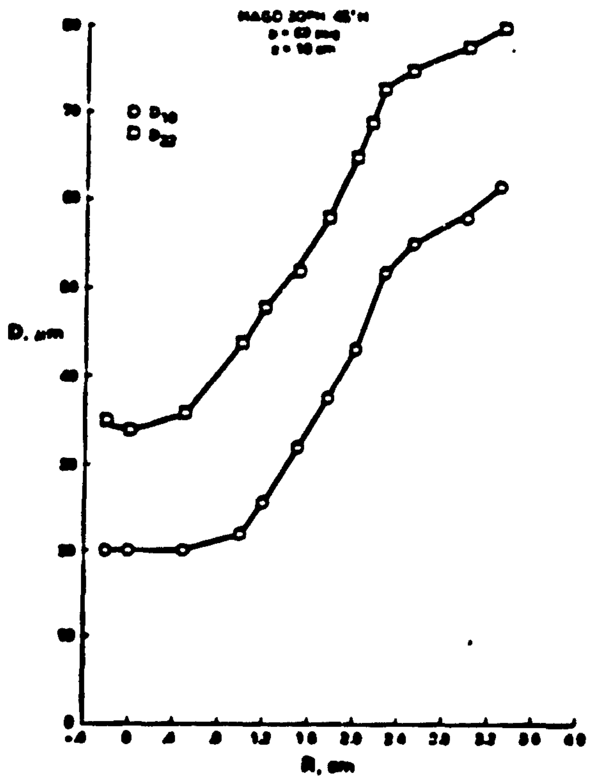


Z = 2 cm.

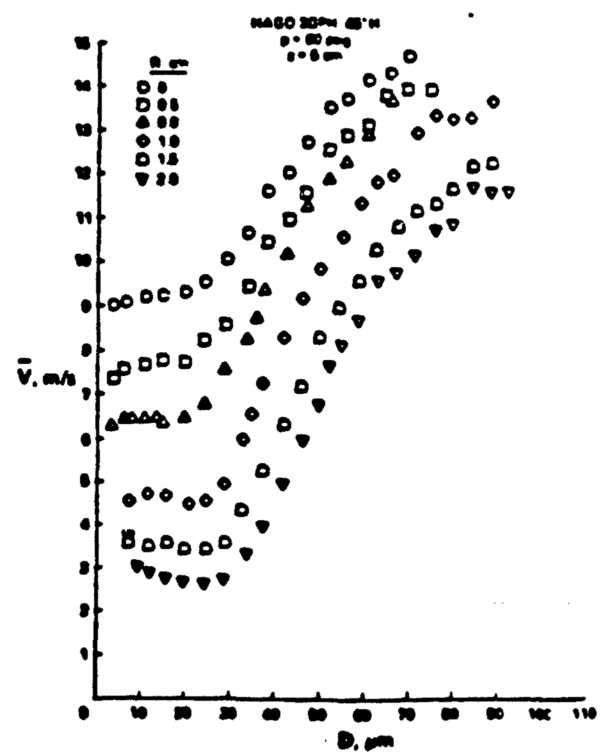


Z = 5 cm.

Radial Distribution of Mean Drop Size



Z = 10 cm.



Radial Drop Size - Velocity Correlations

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In summary, the recognized potential characteristics of the method are:

- linear relationship between the measured phase angle and drop size
- size range of 30 or greater at a single optical setting
- overall size range of 3 to 2000 microns
- simultaneous size and velocity measurements
- relative insensitivity to beam or light scatter attenuation
- high spatial resolution
- operation is similar to an LDV
- adaptable to existing LDV systems
- can distinguish between gas phase and droplets
- reduced sensitivity to misalignment
- can perform measurements independent of refractive index.

A patent application has been filed.

RECENT DEVELOPMENTS

IN MEASUREMENTS TECHNIQUES

- Simultaneous Measurements of Size And Velocity
- Point Measurements In Dense Sprays
- Minimized Impact of Measurement Environment
- Improved Dynamic Range
- Extended Size Range 0.5 to 3000 um
- Spray Flame Measurements

PROBLEM AREAS

RESEARCH OPPORTUNITIES

- Verification of Performance
- Near-Nozzle Measurements
- High Number Density Environments
- Gas Velocity Measurements In Sprays
- Nonuniform Seeding
- Spray Flame Measurements
- Drop Data In Lagrangian Frame
- Measurement of Turbulent Dispersion of Drops
- Communication With Modellers
- Convincing Funding Agencies Basic Data Is Unavailable

END

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